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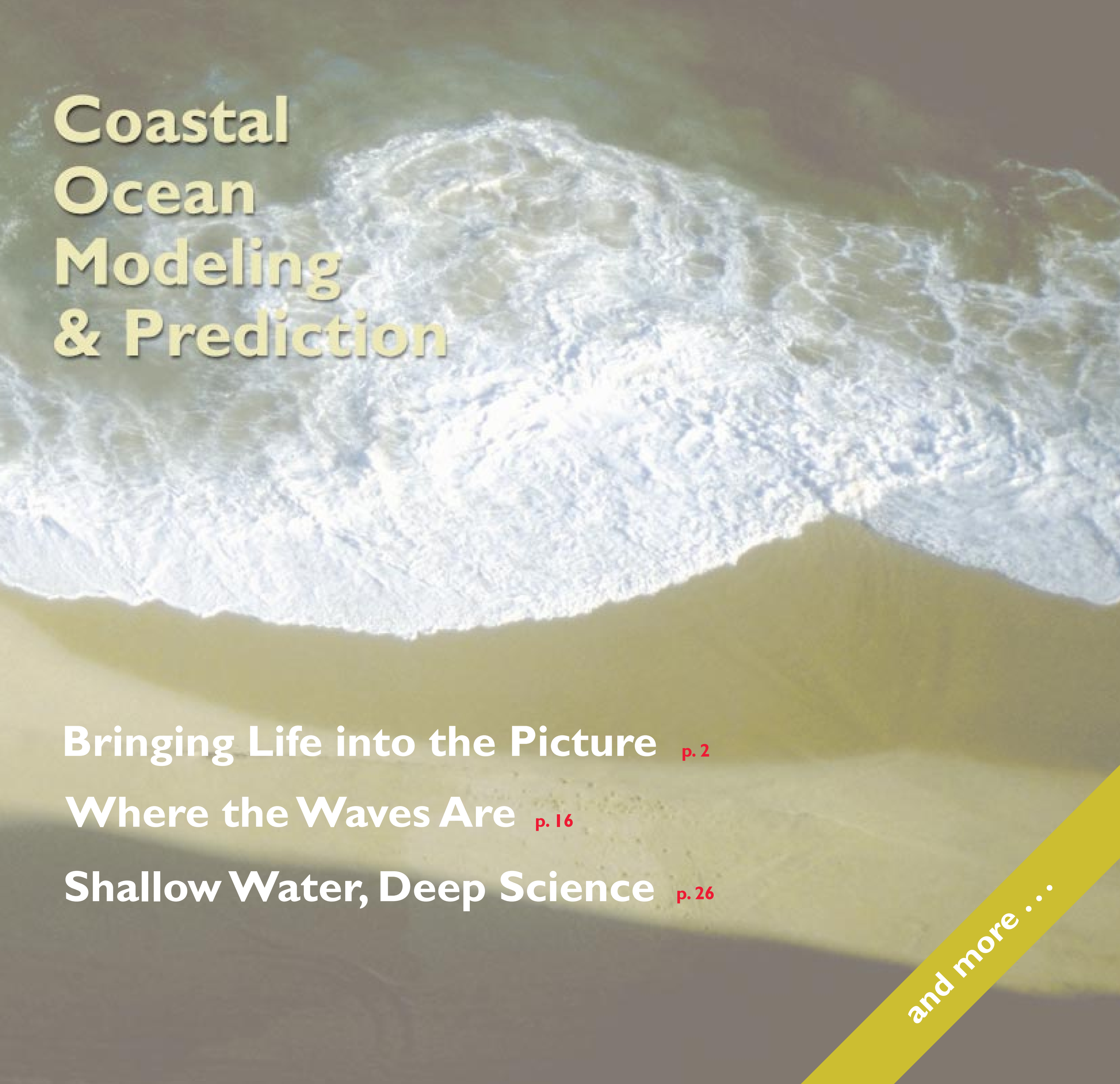


Coastal Ocean Modeling & Prediction

and more . . .

From the Guest Editor . . .

The Navy has growing requirements for real-time, high resolution descriptions of coastal ocean variability. Required resolution relates to ocean features impacting the performance of specific naval systems and sensors. For antisubmarine warfare, such features may be mesoscale fronts and eddies on one to ten kilometer scales. For nearshore mine countermeasures and amphibious operations, features may be surf and rip currents with scales of a few meters. Marine meteorology, critical for Naval aviation and surface ship operations, is also influenced by ocean surface properties over a range of scales.

Variables of interest include sound speed fields for range-dependent acoustic performance prediction, water column optical properties for imaging and visibility applications, ocean current fields for drift estimates and diving operations, wave and surf conditions for beach landings and sea surface temperature and roughness for range-dependent radar performance prediction.

The Office of Naval Research (ONR) supports research and development of ocean nowcast/forecast systems over a hierarchy of scales from global to surf zone. A major focus is on relocatable systems applicable to variability in littoral regions around continents, islands and semi-enclosed seas on time scales of hours to days. Forcing by accurate winds and heat fluxes over domains with adequately resolved bathymetry and coastlines is essential.

All nowcasts and forecasts are imperfect estimates of the true state of the ocean. Specifying and minimizing error are central issues. Sources of error include the inherent limits to predictability of complex dynamical systems, emergent effective properties parameterizing interactions with unresolved scales, and fluxes across discontinuous boundaries. Coupled model-observation systems assimilating data from real-time adaptive sampling produce the most skillful forecasts. Current research focuses on effective and efficient data assimilation, dynamically consistent model initialization, model validation, quantitative measures of forecast skill, model-driven adaptive sampling with feedback, treatment of open boundary conditions including multi-scale nesting, coupling of atmosphere and ocean models, and coupling of acoustic and electromagnetic transmission models to circulation models.

Measuring the skill of ocean nowcast/forecast systems is fundamental. Performance metrics objectively reveal and differentiate the behaviors of the numerics, physics, and parameterizations and their relative impact in the system's ability to estimate reality. Coastal predictive skill experiments currently in progress make it possible to explore objective performance tests based on common core measurements, for example: meteorolgical fluxes, bathymetry, Lagrangian/Eulerian transports, eddy kinetic energy, sea surface topography, water mass properties and phenomenological structure. A practical, objective set of baseline metrics utilizing analytical solutions, numerical simulations and observational case studies is under construction.

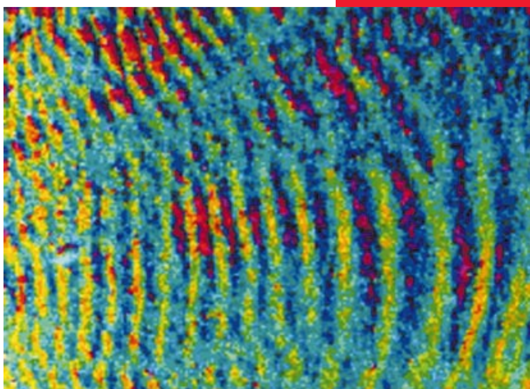
Enabling technologies include massively parallel processor and distributed memory computers combined with autonomous ocean sampling networks using mobile platforms for spatial gradient mapping and adaptive sampling. Research on network simulation and control that is fully coupled with ocean model input/output is underway. An open, adaptive architecture driven by evolving geophysical error constraints is a design goal.

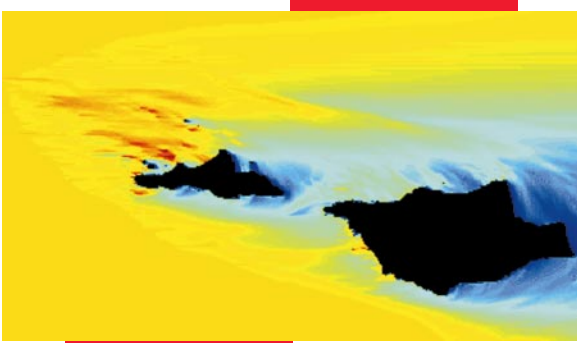
Coastal ocean modeling and prediction research and development is performed in universities, the Naval Research Laboratory (Stennis Space Center, Mississippi and Monterey, California), other Navy and government laboratories, and industry. A principal mission is to transition improved analysis and prediction tools to the operational Navy. To facilitate transition of products to Commander Naval Meteorology and Oceanography Command organizations, such as the Fleet Numerical Meteorology and Oceanography Center and the Naval Oceanographic Office, ONR coordinates its research efforts with the Space and Naval Warfare Systems Command (SPAWAR) Battlespace METOC Data Acquisition, Assimilation, and Application Program funded by the Oceanographer of the Navy. The challenge of advancing the state-of-the-art in operational ocean modeling and prediction involves science, engineering, interdisciplinary collaboration, systems integration, procurement, training, maintenance and feedback.

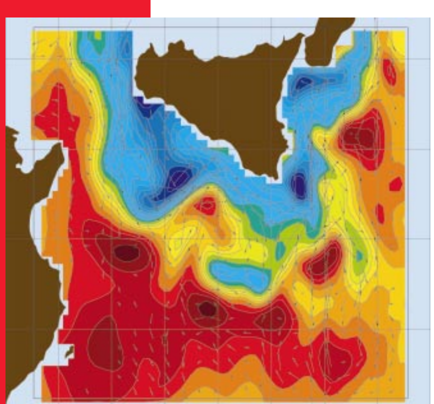
This issue focuses on selected topics in basic research and exploratory development. The state-of-the-art in data assimilation and adaptive sampling are reviewed. An example of high resolution, finite element modeling is included. Such models are particularly relevant to coastal applications with complex geometry. Understanding and trends in surface gravity wave research are examined. The issue is not meant to be comprehensive, but rather to provide a flavor of some important current activities contributing to improved coastal ocean prediction.

Tom Curtin
Office of Naval Research

NAVAL RESEARCH REVIEWS







Bringing Life

Building a realistic model of the coastal ocean is still a long way from reality—but scientists believe they are on the threshold of that possibility. In the past, scientists have approached the challenge by modeling the physical and biological aspects of the environment separately. While physical models have progressed to a high degree of realism, biological modeling is just now blossoming due to advanced computer capabilities. Coupled physical-biological modeling—where the biological model depends on output from the physical model—is an ultimate modeling goal. Military and civilian scientists are interested in developing models that include both the physical and biological aspects of the coastal ocean in this coupled manner.

As the Navy and Marine Corps are increasingly concerned with operating in the littoral, or coastal, regions, their interest in understanding the biological phenomena in

into the Picture

these waters has grown correspondingly. The Navy traditionally has used physical models for ocean forecasting. Coupling these powerful tools to biological modeling will help decision-makers assess the potential effects of naval operations on local biology. The Navy-Marine Corps team is far from indifferent to environmental issues, which occupy them not only during combat—recall the concerns during the Gulf War over Iraqi ecological vandalism—but also during peacetime. Most naval operations are carried out during peacetime under civilian regulations. Concern over the effects of an oil spill on local marine life, ability to predict hazardous algae blooms, understanding zooplankton population dynamics, controlling greywater discharge, and so on, are no longer fringe issues.

In this article, Daniel Lynch discusses physical modeling techniques and how they might be coupled to biological models. Lynch's suggestions offer researchers some interesting directions for future work.

- D.B.

Coupled Physical/Biological Models for the Coastal Ocean

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Abstract

Prospects are reviewed for site-specific models, which couple physics and biology. Physical models have advanced to the point where real-time operational systems (combining land- and ship-based elements) can be built with entry-level resolution relative to biological needs. Coupling biology to these presents a vast frontier of opportunity. Some general and simple guidelines are offered in a hierarchy beginning with abiotic motion and moving progressively through several biotic features: behavior, growth and development, and reproduction. Examples from the Gulf of Maine are provided.

Introduction

This discussion concerns models, which simulate biological processes occurring within, and influenced by, a nontrivial physical environment. We begin with the premise that spatially explicit models are desirable. This is evident from several perspectives. First, all data is obviously spatially explicit. Second, all ecosystems are spatially explicit and each occupies a potentially unique niche in parameter space. And third, all-important operational questions including ecosystem management and emergency decision-making are fundamentally tied to a specific system and its details. We therefore address the notion of constructing spatially explicit, coupled physical-biological simulations.

SPATIALLY EXPLICIT MODELS. Models that portray phenomena within real shelf systems, with realistic topography, forcing, and biota.

The simulation of the physical environment in the coastal ocean has now advanced to a high degree of sophistication and realism. We are endowed with a set of canonical equations; several decades of progress in computational mathematics and machinery; remarkable advances in observational technology; and, an emergent cohort of bright, energetic computational scientists. All of these support the conjecture that skillful spatially explicit circulation models can be constructed and operated in many of the world's coastal oceans. The importance of this cannot be overstated: that it is possible to construct a 4-D (three space dimensions plus time) physical environment comprising motion, turbulence, and hydrographic fields at "entry-level" resolution (order 1 km). This sets the stage for spatially explicit coupled models. And because the coupling is strictly one-way in the oceanic context — i.e. physics affecting biology but not vice-versa — continued progress in physical simulation has a momentum of its own which will lead to continuous improvements in simulated physical environments.

Biological simulation of the coastal ocean is, relative to its potential, far less advanced. The potential biological state-space is enormous and in practice not realizable on any computer; and while some canonical sets of equations have emerged, their parameterization remains elusive in realistic systems. Further, the biological observational base is generally far less developed than its physical counterpart. As a result of this, many biological simulations will necessarily be posed, parameterized, initialized, and forced by hypothesis rather than from observation. The vague question 'what are the dynamics of the biological system?' is not generally meaningful under these conditions.

Despite these difficulties, extremely valuable site-specific coupled simulations can be constructed. Clearly, it is necessary to simplify the biological relationships being modeled if any practical progress is to be made. The most potent simplifications are those that accompany clarification and refinement of specific hypotheses. Given that a "comprehensive" coupled model is not possible, what ideas can be examined with the tools at hand, which include a 4-D site-specific physical environment? Pursuit of scientific objectives along this direction can lead to very productive and revealing coupled simulations. The very fact that biological simulation is less advanced means that the most exciting opportunities are likely to occur along this frontier.

We thus arrive at a practical view of coupled physical-biological simulation, which emphasizes problem-driven simulations in a site-specific context. The principles are:

- use the best available circulation model to provide a site-specific realistic physical environment; know its strengths and weaknesses;
- know the organisms under study – their basic life histories, their patterns of abundance and distribution, and their mysteries (Mangel, 1993);
- formulate the least complex biological model needed to answer focused questions about the system which can be tested against observation. It is likely that these will initially center around space-time relationships relevant to specific organisms or assemblages, implied by the circulation;
- seek and accept inescapable conclusions from the simplest modeling exercises needed to support them; and
- refine the biological questions carefully, building a hierarchy of inference. A likely hierarchy suggested below is to begin with abiotic (passive tracer) simulations, then to add behavioral features, and finally to add feeding and reproduction.

Below we will illustrate these ideas in the context of an ongoing study of the Gulf of Maine system.

Modeling Physics

Gulf of Maine: The Gulf of Maine is a semi-enclosed coastal sea on the eastern North American shelf, stretching from the Cape Cod Islands eastward to the Bay of Fundy and the Nova Scotian shelf, and from the coast of Maine/New Brunswick seaward to the shelf break on the southern edge of Georges Bank.

The basic Gulf-wide circulation is depicted in Figure 1 – a composite schematic that summarizes numerous observational, theoretical, and modeling data. Many important shelf processes are operative in the Gulf, including two primary and distinct inflows across the Scotian Shelf and through the Northeast Channel; deepwater formation in the three major Gulf basins; tides, tidal mixing, and tidal rectification; wind; stratification and frontal circulation; freshwater inflow along the coast; and local estuarine processes.

The Gulf has served as a development laboratory for the Dartmouth Shelf Models for a decade. Fortunately, we have been guided by earlier seminal work by D. Greenberg and colleagues (Greenberg, 1990). These studies defined the basic barotropic modes of the system and established many essential modeling principles for the Gulf, which remain relevant and "right" today.

Nested and Graded Meshes: In a survey of contemporary simulation experience, Lynch *et al*. (1995) observed that achieving adequate resolution in coastal ocean simulations remains a widely shared concern. In the Gulf of Maine, for example, tidal rectification and frontal circulation can demand resolution of order 1-2 km, while properly equilibrated inflows from the Scotian Shelf demand upstream spatial coverage of order 4 shelf widths, i.e. horizontal coverage of order 1000 km. Similarly in the vertical, proper resolution of surface and bottom heat and momentum transfers demands vertical resolution of order 1 m, with total depth reaching 300 m in the Gulf basins and 1000 m or more at the shelf break. Uniform gridding over these ranges produces an estimated 250,000 horizontal cells, with perhaps on average 200 vertical cells. Coupling these spatial needs with the requirements of simulating nonlinear dynamics in tidal time produces a formidable computational challenge.

General Circulation During Stratified Season

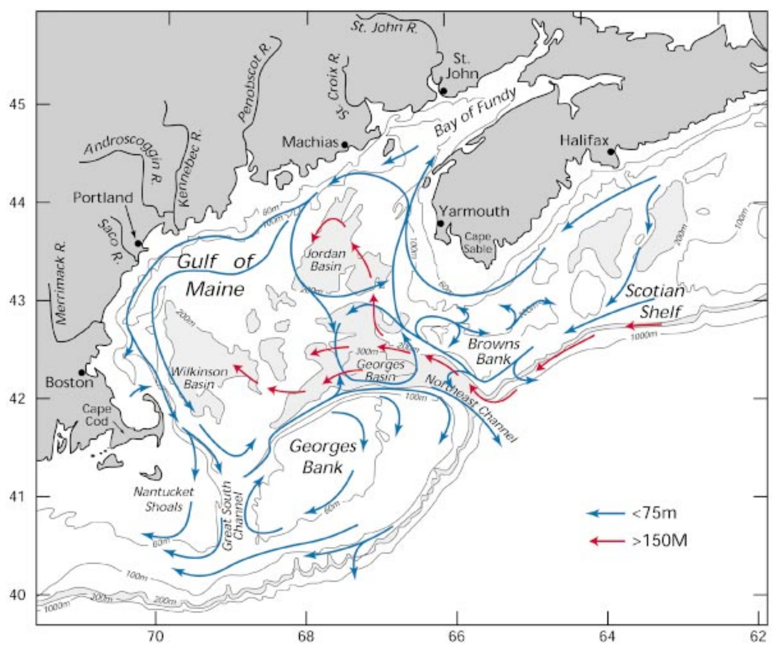

Fig. 1 – Gulf of Maine topography and circulation. [Source: McGillicuddy *et al.*, 1998]

We have used the finite element method to meet this challenge. In this method the horizontal is discretized in unstructured grids of triangles. This permits the use of freely variable resolution to fit topography and circulation features;

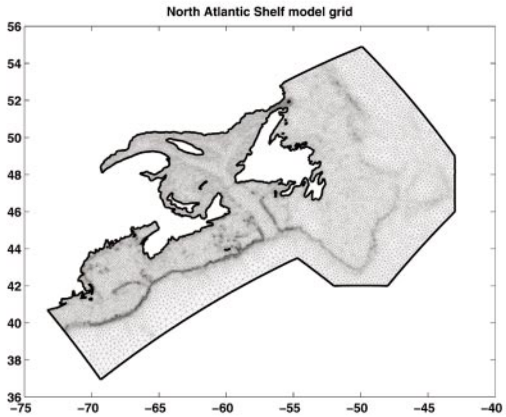

Fig. 2a – Northwest Atlantic Shelf mesh. [Source: Greenberg *et al.,* 1998]

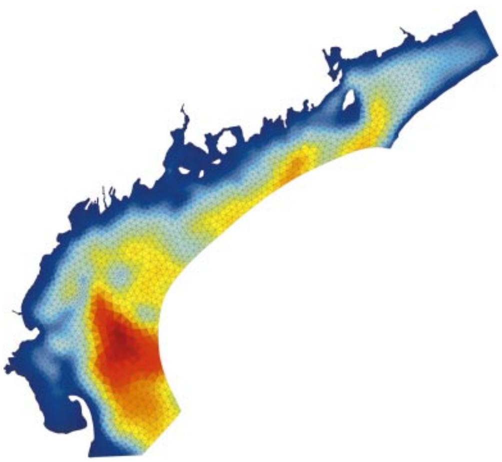

Fig. 2b – Maine Coastal Current mesh. [Source: Lynch *et al.,* 1997]

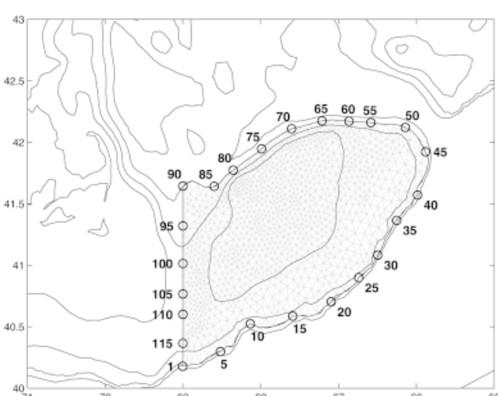

Fig. 2c – Georges Bank mesh. [Source: Lynch *et al.,* 1998]

seamless nesting of near-and far-field domains; and locally enhanced resolution for detailed studies coupling biological and physical processes.

Figure 2a shows an example mesh that covers the Gulf of Maine plus the Gulf of St. Lawrence and the Grand Banks. This mesh is configured for separate or coupled studies of these regions. Our primary Gulf of Maine domain lies within it, extending from the Laurentian Channel to the western tip of Long Island, and seaward to roughly the 1000 m isobath, beyond which it terminates in a gently sloping idealized ocean. Baseline resolution on Georges Bank is of order 3 km, and approaches 1-2 km across the steep northern flank. The flexibility of the finite element method allowed us to fill this domain with only 6756 horizontal nodes and 12877 triangles as a baseline mesh.

Several refinements and alterations have been added for individual studies. Examples of sub-meshes appear in Figures 2b, c for the Maine Coastal Current and Georges Bank. We have used these smaller, more refined meshes in a nested fashion, driving open water boundary conditions with the results of larger-domain simulations. Some experiences with the nesting are reported by Lynch *et al*. (1997); and with mesh refinement, by Lynch *et al*. (1995) and Luettich and Westerink (1995).

The finite element method has served remarkably well in this capacity. It supports a single wide-area calculation with variable resolution; and facilitates nested calculations by making possible natural (e.g. topography-following) terminations of local meshes. And overall, the highest possible resolution is achieved by avoiding wasted resolution, which inevitably results from structured-grid approaches.

Climatology, Hindcast, Forecast: Our earliest modeling experiences have concentrated on the production of a climatology for the Gulf. This occupied considerable energies in the assembly of forcing data, the establishment of boundary conditions, mesh refinement, and finally scrutiny of the solutions. The end result has been the archival of a standard climatology realized as a sequence of six bimonthly realizations of tide and subtidal residual flow fields (Naimie, 1995; Lynch *et al*., 1996, 1997). These are displayed in Figure 3. The general circulation features displayed in figure 1 are clearly present: a cyclonic circulation around the Gulf with substructures over the deep basins; anticyclonic circulation over Georges Bank with partial recirculation; and throughflow from the Scotian Shelf. The seasonal modulation of these features is significant. To date this climatology and its diagnostic predecessor have been compared with moored current measurements (Lynch *et al*., 1993; Naimie *et al*., 1994; Naimie, 1996); turbulence dissipation rates (Horne *et al*., 1996); and drifter trajectories (Naimie *et al*., 1999) with satisfying results.

This climatology has been used in numerous coupled

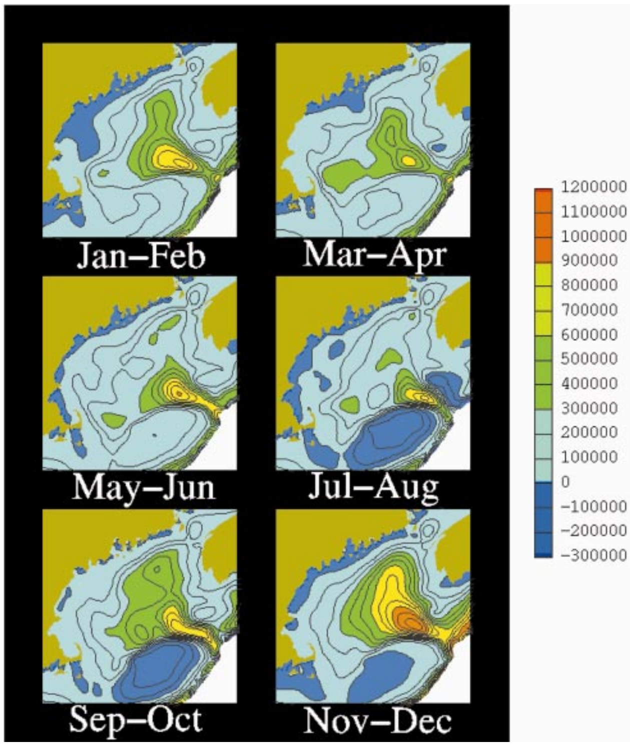

Fig. 3 – Gulf of Maine climatological circulation. Illustrated is the streamfunction governing mean subtidal flow in each of six bimonthly seasons. Contour interval is 0.1 Sverdrup. [Source: Naimie, 1995]

physical-biological studies to date, some of which are reviewed below. The premise in this type of modeling is that long-term mean tendencies of the coupled system can be "explained" by the union of average physical fields and average biology. This is not to say that either the physics or the biology is linear or lacks variation; only that at the points of coupling, the climatological mean interaction is prominent in the mean outcomes. If we conceptualize the biological and physical fields as the sum of climatological means (m, n) and variations (d, e) about those means, then their average interaction would have two contributions: the mean interaction mn plus the covariance E(de), a Reynolds' stress-like term. Failure of the mean interaction to replicate long-term system tendencies is an indication that the covariance of physics and biology is important. In itself this would be a substantive conclusion.

The climatology is the starting point for several subsequent investigations. Containing as it does a complex set of 4-D structures with seasonal modulation, it constitutes the best prior estimate for circulation at any particular time. In the absence of observations, this estimate is the only substitute for the null case (zero motion) which would be a foolish choice. Beyond climatology, we have two types of physical simulations: hindcast and forecast. In both cases the problem is to make reasonable adjustments to the climatology to fit specific observations.

An example of a hindcast is shown in Figure 4. In this case we were concerned with hindcasting the detailed circulation on Georges Bank during a 2-week period for which both hydrography and CTD data were available. The general procedure is to force a prior estimate with climatological boundary conditions and observed wind, heat flux and hydrography. Adjusting the open-water boundary conditions minimizes discrepancies between simulated and observed velocities. Figure 4a shows the observed velocity; tides are dominant. The remaining unexplained velocity, post-hindcast, is depicted in Figure 4b. In essence this is a least-squares problem, with a nonlinear forward model. It is solved iteratively as in Figure 5. The availability of a fast, linearized inverse is critical. Details can be found in Lynch *et al*. (1998).

The forecasting problem is distinguished by the timing of data availability and the necessity of making a sequence of simulations, each assimilating a growing observational base (Figure 6). In April-June of 1999, the first Gulf of Maine

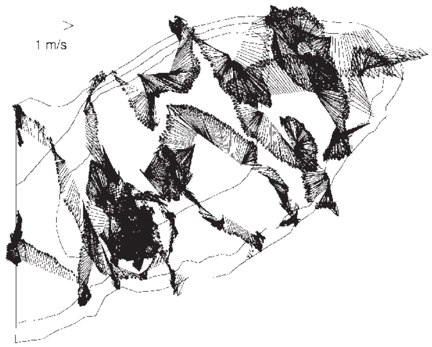

Fig. 4a – Observed ADCP data for cruise EN265 on Georges Bank. [Source: Lynch *et al.,* 1998]

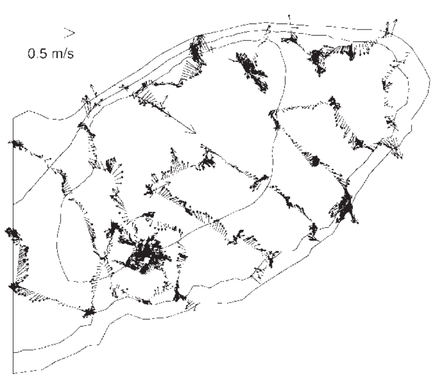

Fig. 4b – Residual (unexplained) velocity after inversion of EN265 ADCP data. This is the discrepancy between modeled velocity and the data in figure 4a, following assimilation. Note the change in scale from figure 4a. [Source: Lynch *et al.,* 1998]

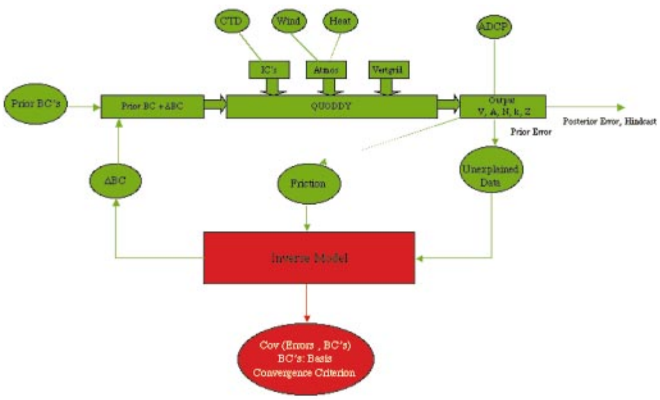

Fig. 5 – Inversion procedure. The forward model QUODDY (green) is a comprehensive 3-D simulation with full nonlinearity and advanced turbulence closure. The inverse model (red) is based on a linearization of the forward. It deduces boundary condition improvements needed to minimize the unexplained velocity data. Because of the nonlinearity, the loop is closed by iteration.

operational modeling exercise was carried out at sea, with daily forecasts of the Georges Bank circulation. This real-time assimilation procedure is using a climatological prior estimate of forcing and circulation; sequential forecasts of atmospheric forcing and related oceanic wind-band pressure boundary conditions; and assimilation of CTD, drifters, and ADCP data into forecast products on the local mesh shown in Figure 2c. The experiment showed that using today's workstations, a 3-day limited-area forecast can be computed at sea within a half-day of the closing time for atmospheric data; and that forecasts could be expected to predict drifter trajectories within a few km over a few days. Archived results from this at-sea experience will provide an experimental testbed for evaluating different assimilation strategies.

These and other experiences support the position that site-specific real-time operational systems, combining land- and ship-based elements as in Figure 7, can be built with entry-

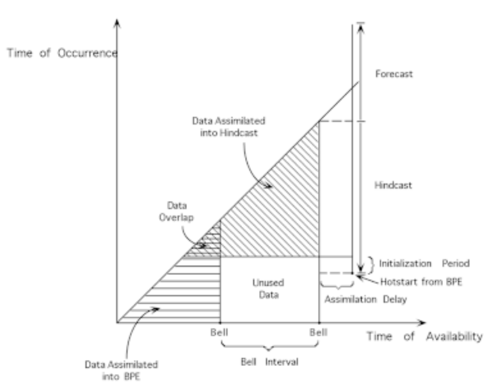

Fig. 6 – Forecast system time lines.

level resolution relative to biological needs. The design skill lies in assembling the right combination of prior estimate, networked instruments and databases, and interactive nesting/refinement of calculations to support specific tasks.

Observational System Simulation Experiments:

Perhaps the most challenging opportunity for modeling today

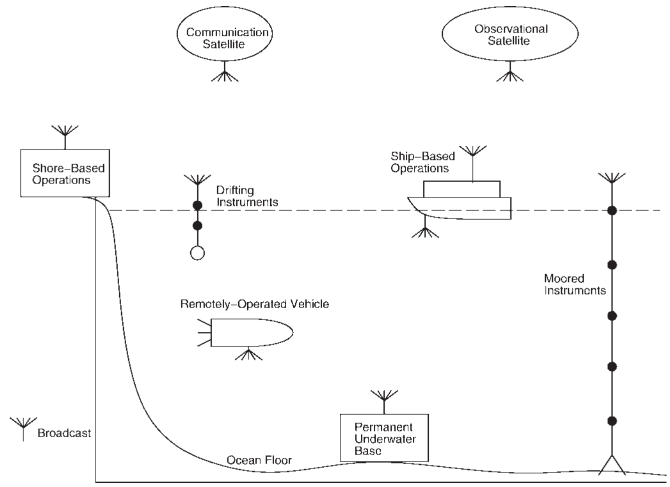

Fig. 7 – The future of ocean modeling. Data will be obtained from a variety of networked instruments and services and integrated seamlessly into data-assimilated simulations running concurrently on land- and ship-based platforms.

is in the design of field sampling plans. A realistic site-specific simulation can be used as "truth" and sampled according to a real or proposed sampling program. Measurement error may be incorporated into the model output sampling. These measurements may then be used to reconstruct the circulation using a candidate assimilation procedure, and the errors in the reconstructed field quantified against the "truth." This general idea provides a complete evaluation of sampling plan plus assimilation procedure, and is a gateway to exploring the limits of inference imposed by practical computational and observational equipment, as well as available theory. OSSE's are the practical design tool for the construction of systems as depicted in Figure 7.

Observational System Simulation Experiments have been conducted relative to Georges Bank hydrographic (Lynch and Naimie, 1998) and zooplankton (McGillicuddy *et al*., 1999) fields.

Coupling Biology

Assume the existence of a comprehensive physical simulation. What can be done with it, given the litany of difficulties mentioned in the introduction? We suggest starting with the simplest aspects of the coupled system, and working outwards/upwards from there. First we review two basic modeling strategies. Then we suggest an approximate 4-level hierarchy of complexity.

The Physical/Biological Interface: There are two basic approaches for constructing coupled physical-biological simulations. The first, conventional approach mimics that which has been successful in the physical modeling: construct Eulerian fields representing densities of organisms in various categories, and write partial differential equations for their transport and evolution. The canonical form is the advective-diffusive-reactive equation

$$\frac{\partial c}{\partial t} + \nabla \bullet \left[(v + q)c + J \right] = R \qquad (1)$$

with c the Eulerian density, v the fluid motion, J the nonadvective (dispersive) flux, R the net source. An essential additional feature is the behavioral transport vector q, representing active motion relative to the ambient fluid. Note we do not assume anything about its divergence.

Many coupled systems have been cast in this framework (e.g. Franks *et al*., 1986; Fasham *et al*., 1990); computationally it requires only a natural extension of algorithms used to transport physical fields, plus the closure of the biological terms q and R. Experience shows successful simulations with relatively large numbers of Eulerian variables; and in particular nonlinear, density-dependent relations in the source term R are natural computationally. However, the specific rendering of biological ideas about e.g. development and behavior, into closures for q and R, can be awkward, because one is dealing only with an aggregation, not individual organisms per se. We refer to this modeling strategy as the Eulerian or Concentration-Based Model (CBM).

A distinctive alternative is the Lagrangian, Individual-Based Model (IBM) (DeAngelis and Gross, 1992). In this approach, one simulates individual organisms separately, writing a set of ordinary differential equations for individual evolution through physical (x) and biological (b) spaces:

$$\frac{dx}{dt} = v(x,t) + q(x,b,t) + \varepsilon_x \qquad (2)$$

$$\frac{db}{dt} = f(b,x,t) + \varepsilon_b \qquad (3)$$

The terms ε are stochastic terms representing individual variability. The basic formulation is for each individual; the population is the assembly of many such individuals, appropriately initialized. This formulation provides a direct and natural means of simulating specific organisms with specific behavioral and other relationships to the environment. Incorporation of experimental information can be quite natural in this setting; and natural variability in biotic processes is easily incorporated through the stochastic terms. As a result, detailed biological resolution is possible at the level of individuals and populations, provided the balance of the physical and biological system is available as Eulerian fields. (See e.g., Werner *et al*., 1996; Carlotti and Wolf, 1998; Bryant *et al*., 1998). The simulation of density dependence is fundamentally problematic in this approach, as it poses a classical n-body problem, which can be very unfavorable for large systems.

Both types of models are in common use; see the recent issue of Fisheries Oceanography (Coombs *et al*., 1998) for a sampling of contemporary applications. We have used both to advantage in the Gulf of Maine work described below. Because of their complementary strengths and weaknesses, a mature simulation is likely to have both types of models interacting; for example an IBM approach to specific target species, coupled to a more general CBM model for the balance of the ecosystem.

Considerable care must be exercised in the specification of the random variables ε. The biological variation represents a substantive aspect of the system and an opportunity to exploit the natural strength of the IBM approach. The motion variation is typically treated as a random walk process, with parameters derived from the modeled hydrodynamic turbulence. Although this is simple in the case of uniform mixing, such is rarely the case in the coastal ocean. The specification of random walk models in heterogeneous media is a significant subject in itself and several detailed studies are available. (Thompson, 1987; Hunter *et al*., 1993; Okubo, 1986). The simplest generalization to the inhomogeneous case is likely to have the unintended consequence of concentrating individuals in low-mixing areas, an unphysical result.

Motion and its implications: The first, baseline requirement is "know your circulation fields". Given the availability of 4-D physical fields (motion, turbulence, hydrography) on complex topography, there are millions of space-time trajectories of potential interest. These can be explored with the simplest abiotic models. Doing so in a way that illuminates biological issues is the first level of coupled modeling – in this case, coupling the physics to a biological question. It is important to give this seemingly elementary step its proper respect. The motion imposes a set of potentially complex space-time patterns as an abiotic- or null-model baseline. Understanding and recognizing them is critical. Contributing to these patterns are

- the basic advective pathways in the system and the space-time relations which they imply for organisms;
- the presence of convergence/divergences in the flow and their ability to concentrate organisms;
- the basic residence times for organisms entrained in various circulation features;

- the impact of spatially variable hydrodynamic dispersion – either shear dispersion or eddy diffusivity.

As an example, we recently completed a study of *Calanus finmarchicus*, a dominant copepod in the Gulf of Maine. This animal is observed in population centers in the deep basins of the Gulf during summer, with development arrested in a nearly mature developmental stage (diapause). Activation in the December/January timeframe results in the individuals moving toward the surface, maturing to adulthood and beginning the production of two to three generations of offspring prior to the end of the growing season, perhaps June. The offspring move through 12 developmental stages, with the earliest stages presumed important in the diet of larval Cod and Haddock. Questions surrounding this population include the relationships among time and place of activation and the subsequent pathways to the bank; the vital rates along these pathways; the space-time patterns of *Calanus* occurrence on the bank, especially the production of the earliest offspring; and the presence or absence of self-sustaining annual pathways which would return offspring to the deep basins from which their grandparents originated.

Many of these issues can be addressed with carefully constructed passive (or nearly passive) tracer studies. In particular, the initial resting stock may be expected to live for 2 months or more, and therefore a simulation of their transport alone, subject to baseline mortality (decay), is a simulation of the transport of reproductive potential. An example appears in Figures 8a, b. These are the results of clouds of passive tracer initially present in one of the deep basins, transported in either the vertically averaged flow or concentrated in a near-surface layer. The outcomes are complex, and different. The surface layer moves about twice as fast and is more effective in delivering animals to Georges Bank; the vertically averaged flow is slow and follows the deeper topography. Additionally, the surface layer concentrates surface-seeking organisms at downwelling zones which create transport lanes and aggregation hot spots. And, the surface layer cloud has developed a bifurcation. Using these and other nearly passive simulations, we have been able to confirm that the deep basins of the Gulf are capable of populating most of Georges Bank, each having its own distinctive space-time signature. Inflow from the Scotian Shelf also contributes to the Southern Flank of the Bank in its own characteristic pattern.

These passive features are the manifestation of fundamental constraints on all of the coupled physical/biological outcomes. It is important to accept them as natural tendencies of the system. Comparison with available data allowed the refinement of a three-layer, 3-field model accounting for the initial generation -- a deep immobile reservoir of resting copepodites; an intermediate layer of copepodites exiting diapause and transported in the vertically averaged flow; and a surface layer of newly-molted adults. These simulations allowed us to deduce the size of the previously unmeasured near-bottom population, from the observed persistence higher in the water column; the unmeasured population appears to be comparable to that measured. A related conclusion is that source regions in the Gulf provide a persistent, rather than an impulsive, loading of adults to Georges Bank. The exit from diapause appears to be prolonged over 2 months.

Finally, any activation of adult reproduction in this model led immediately to an undeniable problem: although the adult populations were correctly placed in space/time, the offspring were far too early relative to the data. The most likely explanation for this phenomenon emerged as a reproductive delay due to limited food supply during the transit from the deep basins to the Bank; and this is consistent with observations of primary productivity. The resulting conceptual model is summarized in cartoon form in Figure 9.

Behavior as an adjunct to the hydrodynamic motion: The above case study calls attention to biological behavior as an important mediator of the motion. The passive tracers which are confined to the surface layer move faster and in different directions than their depth-mean counterparts, and show the concentrating (diluting) effect of layer convergence (divergence). Implied is a behavioral assumption that the animal being modeled can regulate its depth in a complex physical environment — in that sense, it is not passive at all.

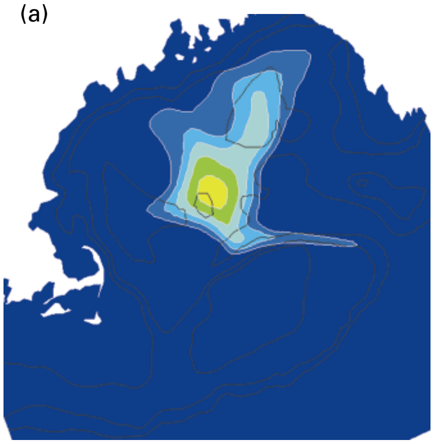

Fig. 8a – Passive transport of *Calanus* initialized over Jordan Basin; vertically-averaged flow. [Source: Lynch *et al.,* 1998]

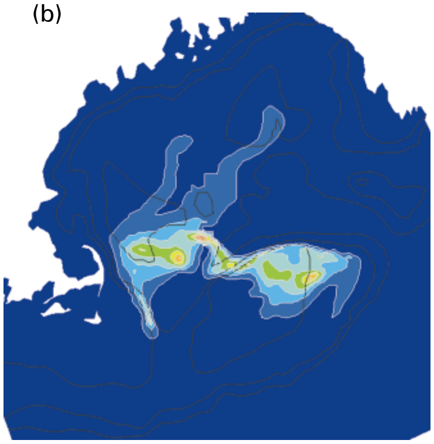

Fig. 8b – Same as figure 8a, but the cloud is confined to a 25-meter thick surface layer. [Source: Lynch *et al.,* 1998]

As a rule of thumb, individual organisms can be expected to sustain swimming of the order one body-length per second. This adds a behavioral transport vector to the hydrodynamic transport; and as in the hydrodynamics, it can be divided conceptually into advective (mean individual tendency) and non-advective (individual variability) parts. Closure of this behavioral transport in terms of the physical environment (velocity, turbulence, light, stratification), the biotic environment (food, predators), and the target organism itself (developmental stage, nutritional status, prior stress, etc.) is a fundamental issue for any biological simulation in a complex circulation field.

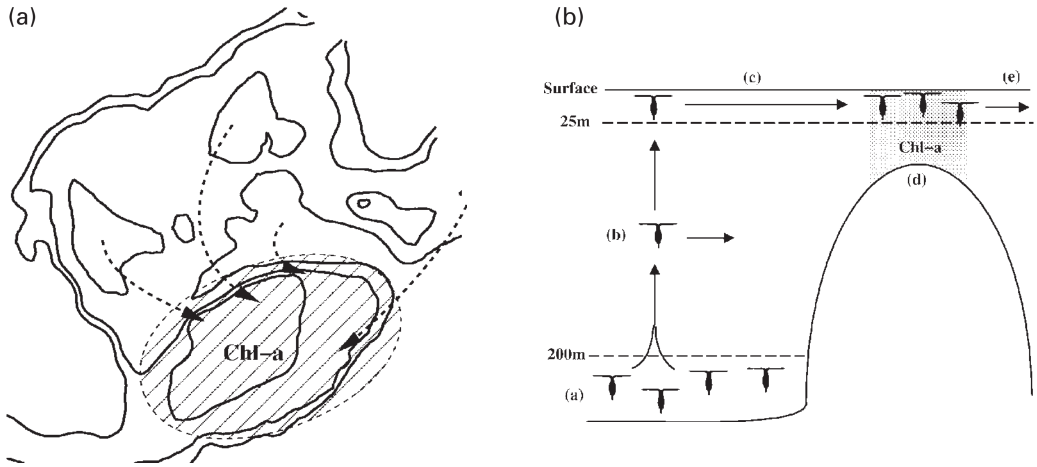

Fig. 9 – Conceptual model resulting form the union of simulation and *Calanus* data: a) horizontal; b) vertical. [Source: Lynch *et al.,* 1998].

As an example, Werner *et al*. (1993) simulated the egg and larval stages of Cod and Haddock spawned on Georges Bank using simple IBM's. Initially, observed depth distributions were used to close the behavior. It was found immediately that the assumed near-surface positioning of the egg stage resulted in transport off the bank (a fatal trajectory) of the entire cohort; this led to the serious reexamination of the appropriateness of the sparse data for this stage. Generally, these early and inescapable results have endured. Later simulations with refined physical fields and IBM's continue to show near-surface individuals are swept off the bank, while deeper individuals are more likely to be retained and advected to areas with chances for successful survival. Essentially, the right behavior is critical to larval survival in this system.

Comparing these simulations with data, one must guard against an inherent bias toward the survivors. Fundamentally, in nature we are able to observe only the survivors, which for these populations is a tiny percentage. The literature suggested that older larvae in this system preferred deeper positioning, and also horizontal positioning closer to the center of the bank. The simulations indicate that these two tendencies are exhibited by the passive behavioral system, since near-surface trajectories leave the system (die) and deeper (surviving) trajectories which sample the bottom boundary layer have a shoalward tendency. While the passive system does not account completely for these observed effects, it nevertheless highlights the danger in interpreting outcomes of a coupled system in terms of biological behavior alone, especially when the observable outcomes in nature are biased toward the survivors.

As in the case of the Calanus calculations above, these are very simple biological simulations that have provided significant insight about the nature of the system and its observation.

Feeding and development: The individual-based modeling context is naturally extended to include feeding and development, provided there are suitable relations for ingestion and growth, and a suitable model for the prey field. As an example, Werner *et al*. (1996) added an energetic model which balanced food ingestion against metabolic costs to determine net growth for an individual larval fish. The trophodynamic relations in this case were available from rearing studies. These were integrated into the larval fish behavioral IBM described above. The resultant state of each individual therefore consisted of position, weight, and age. The environment included hydrodymanics (velocity and turbulence) and food in various size classes. The spatially variable food data were assembled from historical observations. Example results appear in Figure 10 that express the relative effects of feeding success and transport on larval survival on Georges Bank. Essentially, survival in these simulations requires a) retention in the Georges Bank system; and b) integrated growth in excess of the "death barrier" as illustrated in Figure 10. These simulations called attention to an apparent critical gap in the food supply, whereby simulated first-feeding larvae were systematically undernourished, and to the likely role of other species (e.g. microzooplankton) in the diet at this life stage.

Lynch *et al*. (1999) extended this study by incorporating reproducing populations of two prominent zooplankton species, in order to avoid the sparse observations of the earliest/smallest prey life stages. Using the same IBM for

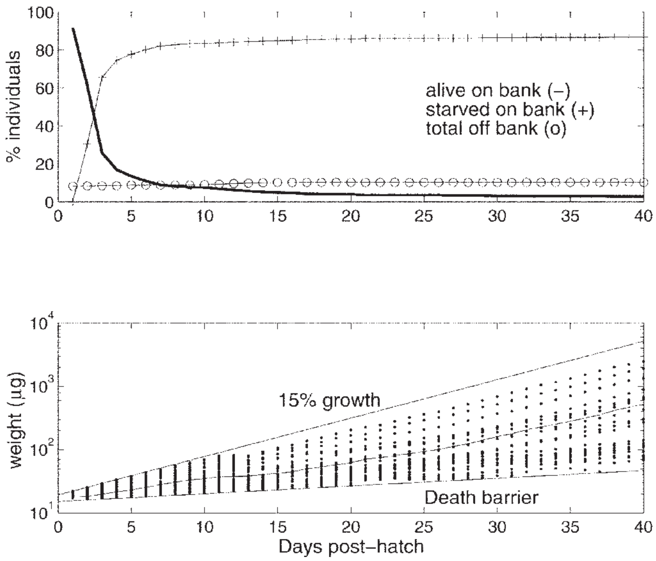

Fig. 10 – Individual-based model simulation of larval fish spawned on Georges Bank. The top panel partitions the losses between advection and starvation. The lower panel shows the growth curve of the survivors. [Source: Werner *et al.,* 1995]

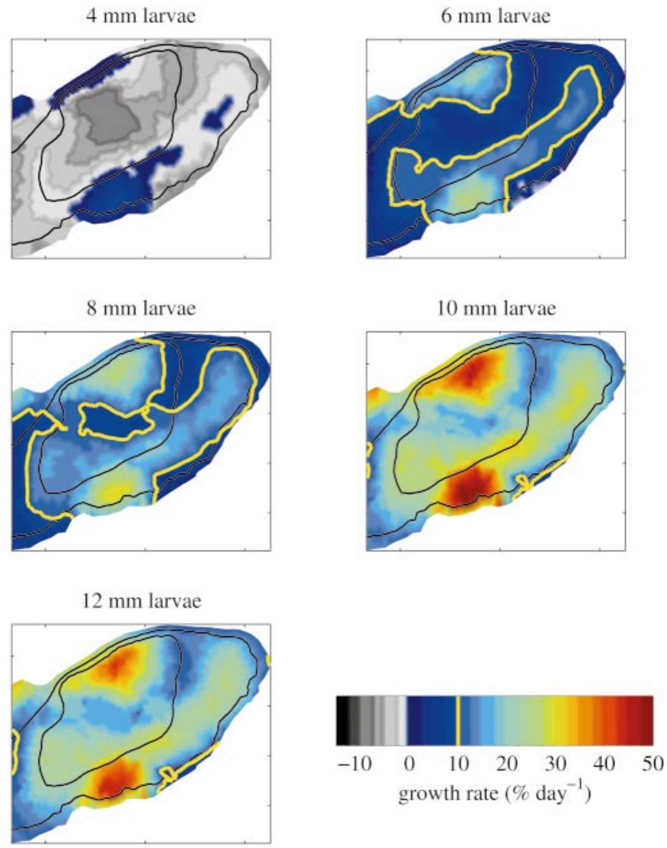

Fig. 11 – Map of larval growth rate on Georges Bank. The growth rates are computed with the larval fish individual-based model; the prey fields are computed using simplified population dynamics and observed adult concentrations of *Calanus finmarchicus* and *Pseudocalanus* spp. [Source: Lynch *et al.,* 1999]

larval fish, and simplified prey population dynamics from Lynch *et al*. (1998) and McGillicuddy *et al*. (1998), maps of feeding rate were constructed for the Bank (Figure 11). These results indicate the surprising opportunity for *Calanus* eggs to be an important dietary item for first-feeding larvae.

One of the findings in this study was the critical role of turbulence in affecting predator-prey encounter rates, and successful ingestion. Increasing turbulence favors the former, but disfavors the latter. The balance of these appears critical to the first-feeding larvae, for which high levels of turbulence has a net negative effect. The turbulent dissipation rate used in these studies was taken from the modeled hydrodynamics as part of the physical environment experienced by the individual larva. Continued study of the proper parameterization of turbulence and its impact on larval feeding is needed.

Reproduction: The larval fish IBM's discussed so far have had no need to close the life cycle, since the period of interest has been limited to the first few months of a surviving individual's full life span. In the zooplankton case, however, the life cycle involves several generations in a single year, and reproduction is a necessary ingredient in a relevant model.

In the Eulerian model such as that described above for *Calanus*, this is incorporated by introduction of separate Eulerian fields for every important development stage. A developmental conveyor-belt effect then occurs as the population ages, with residence times in each stage given as the inverse of the stage duration. In effect we have 'advection' through the conveyor belt. But as in hydrodynamic advection, artificial diffusion inevitably occurs and we obtain premature breakthrough from egg to adult unless the duration in each stage is small. So the control of developmental diffusion can become a limiting computational problem. In Lynch *et al*. (1998) we subdivided developmental stages which had a duration of greater than one day; the result was a total of 87 Eulerian variables to describe the population. Needless to day, this can quickly become a limiting consideration.

The alternative IBM modeling approach is elegantly suited to this problem. In Miller *et al*. (1998) this idea was implemented for *Calanus finmarchicus* in order to simulate the occurrence of up to 3 generations of copepods in a single growing season. Each individual carries a biological state which includes developmental stage and age-within-stage; and matures according to a blend of deterministic and stochastic relationships which can be related to laboratory rearing data. Upon reaching adulthood, the population differentiates sexually, and females begin reproducing

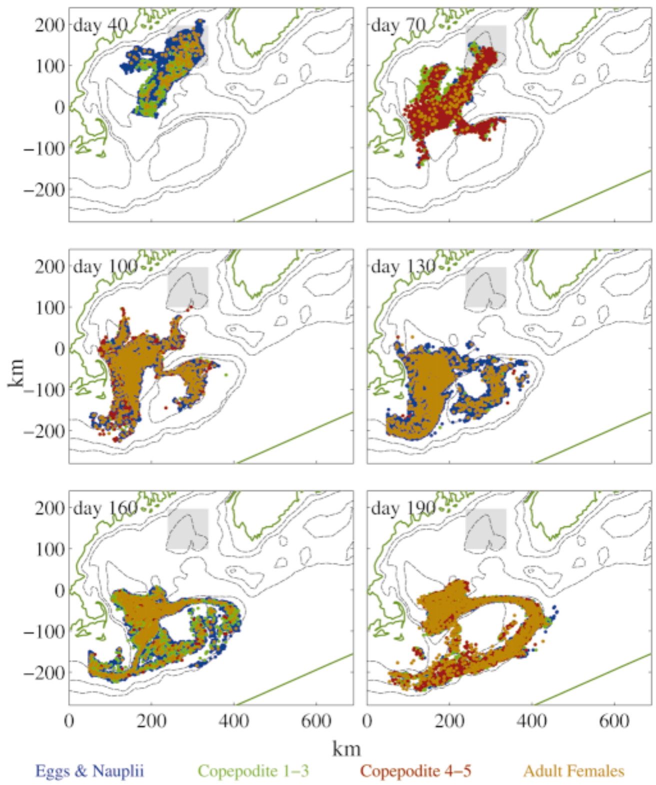

Fig. 12 – Individual-based model for *Calanus* exiting diapause in Jordan Basin. Each adult spawns roughly 50 eggs per day which are transported and mature in the circulation system. A subsample of particle locations are plotted with color indicating developmental stage. [Source: Miller *et al.,* 1998]

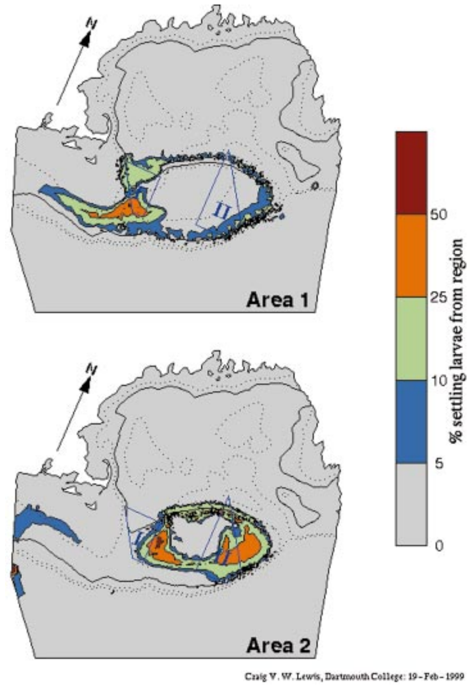

Fig. 13 – Results of 40-day Scallop larval drift from indicated areas, indicating retention and self-seeding charactistics. [Source: Lewis *et al.,* 1999]

depending on their biological state and the environment. Artificial developmental diffusion is completely eliminated in this approach. In addition, individuals may preserve a complete identity including place of birth, origin and status of mother, generation number, and ultimate source population. The only real addition to the IBM technology is the requirement that new particles be 'spawned' as necessary. Care is needed to manage these computations – for example in Miller *et al*. an initial population of order 500 individuals grows to 500,000 surviving individuals over a few months! And many more were spawned and died along the way. When these numbers become too large for simulation, statistical subsampling of the population is necessary (Batchelder and Miller, 1989). Figure 12 shows a typical output of these simulations.

In another example of the same model, we studied the long-term effects of restricted fishing in certain areas (Lewis *et al.*, 1999). In this example we looked at scallops, whose larvae are spawned in the fall, and settle on the bottom after a pelagic period of roughly 40 days. The fall period is a peak recirculation time in the Georges Bank climatology, resulting in relatively high retention of the local population. The operative question in this study concerns the effectiveness of closing certain areas to fishing and the long-run effects on stock rebuilding.

Figure 13 illustrates the retention effect of the circulation over a single 40-day pelagic period within the fall climatology. There is exchange among areas 1 and 2, with area 1 being largely self-seeding and area 2 seeding both areas.

Figure 14 illustrates the long-run consequences of the closed areas. In this calculation, spawning occurs once per year. Initially, adults are seeded everywhere. Larvae drift for 40 days and then settle and remain immobile until the following year when spawning occurs again. Natural mortality is enhanced by fishing mortality everywhere in the left panel; in the right panel, there is no fishing mortality in the closed areas. The mortality and fecundity relations in this simulation are very simple; but the impact of the closure on stock rebuilding is dramatic and invites refined modeling.

Conclusion

Today we are facing enormous opportunities for scientific progress in coupled physical/biological simulations of the coastal ocean. Site-specific physical simulations are advancing remarkably fast, making possible a huge variety of simulations. We are still a long way from being able to claim "comprehensive" simulations on the biological side; and nearly all physical simulations are claiming the need for higher resolution. Nevertheless, by sticking to a few basic principles we can forecast significant model-assisted

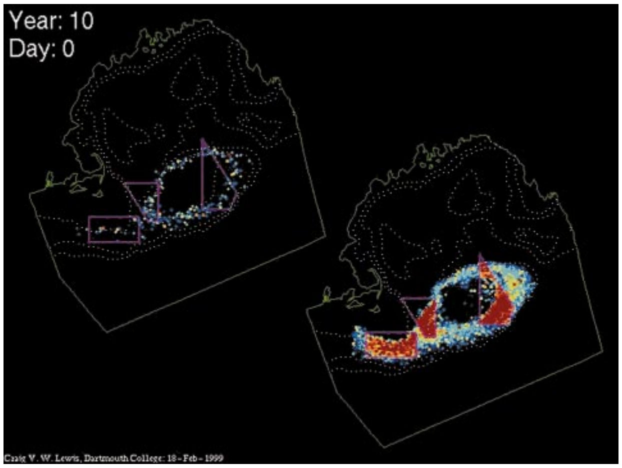

Fig. 14 – Results of a 10-year Scallop simulation. Individual surviving scallops are plotted with color indicating age (red = old). Right panel: fishing restricted in the three closed areas. Left panel: no fishing restrictions. [Source: Lewis *et al.,* 1999]

advances in our understanding of these systems. Among these principles are:

- Know your circulation fields
- Know your organisms
- Ask simple baseline questions focused on specific hypotheses which are testable
- Accept and accumulate the conclusions from these

Implied is a hierarchy of biological complexity, starting with the abiotic (passive tracer) case and progressively adding behavior, development and feeding, and reproduction as necessary.

Finally, it is important to recognize that models do not make important simulations – rather modelers make them. We are fortunate today that there is a developing cohort of high-caliber modeling professionals in ocean science. Their continued encouragement and development is by far the most important priority as we move toward site-specific, coupled simulations on an operational basis.

Acknowledgments

Several individuals have worked with me over the past decade to refine the ideas expressed here. Particularly worthy of mention are D.McGillicuddy, C. Davis, W. Gentleman, D. Greenberg, C. Hannah, M.Holboke, C. Lewis, G. Lough, C. Miller, C. Naimie, I. Perry, and F. Werner, who contributed many of the graphics from the cited papers.

References

1. H.P. Batchelder and C.B. Miller, "Life history and population dynamics of Metridia pacificus: results from simulation modeling," *Ecol. Model*, **48**, 113-136 (1989).
2. A.D. Bryant, D. Hainbucher and M. Heath, "Basin-scale advection and population persistence of Calanus finmarchicus," *Fisheries Oceanography*, **7**(3/4), 235-244 (1998).
3. F. Carlotti and K.U. Wolf, "A Lagrangian ensemble model of Calanus finmarchicus coupled with a 1-D ecosystem model," *Fisheries Oceanography*, **7**(3/4), 191-204 (1998).
4. S. Coombs, R. Harris, I. Perry and J. Alheit (eds.), GLOBEC Special Issue, *Fisheries Oceanography*, **7**(3/4), Sept/Dec (1998).
5. D.L. DeAngelis and L.J. Gross (eds.), *Individual-Based Models and Approaches in Ecology: Populations, Communities, and Ecosystems*, (Chapman and Hall, New York, 1992), p. 525.
6. M.J.R. Fasham, H.W. Ducklow and S.M. McKelvie, "A nitrogen-based model of plankton dynamics in the oceanic mixed layer," *J. Mar. Res.,* **48**, 591-639 (1990).
7. P.J.S. Franks, J.S. Wroblewski and G.R. Flierl, "Behavior of a simple plankton model with food-level acclimation," *Marine Biology*, **91**, 121-129 (1986).
8. D.A. Greenberg, "Chapter 5, Modeling Marine Systems," *The contribution of modeling to understanding the dynamics of the Bay of Fundy and Gulf of Maine vol. 2*, A.M. Davies (ed.), (CRC Press, Boca Raton, 1990), pp. 107-140.
9. D.A. Greenberg, F.E. Werner and D.R. Lynch, "A diagnostic finite element ocean circulation model in spherical-polar coordinates," *J. Atmospheric and Oceanic Technology*, **15**(4), 942-958 (1998).
10. E.P.W. Horne, J.W. Loder, C.E. Naimie and N.S. Oakey, "Turbulence dissipation rates and nitrate supply in the upper water column on Georges Bank," Special Volume on Georges Bank, *Deep Sea Research II*, **43**, 7-8, 1,683-1,712 (1996).
11. J.R. Hunter, P.D. Craig and H.E. Phillips, "On the use of random walk models with spatially variable diffusivity," *J. of Computing Physics*, **106**, 366-376 (1993).
12. C.V.W. Lewis, D.R. Lynch, M.J. Fogarty and D. Mountain, "Effect of Area Closures on Georges Bank Bivalves: Larval Transport and Population Dynamics," http://www.nml.dartmouth.edu/~lewis/closed_areas/index.html, 25 February 1999.
13. D.R. Lynch, A.M. Davies, H. Gerritsen and C.N.K. Mooers, "Closure. Quantitative Skill Assessment for Coastal Ocean Models," *Coastal and Estuarine Studies*, American Geophysical Union, D.R. Lynch and A.M. Davies (eds.), **47**, 501-506 (1995).
14. D.R. Lynch and C.E. Naimie, "The M2 Tide and its Residual on Georges Bank," *J. Phys. Oceanography*, **23**, 10, 2,222-2,253 (1993).

15. D.R. Lynch, J.T.C. Ip, C.E. Naimie and F.E. Werner, “Convergence Studies of Tidally-Rectified Circulation on Georges Bank,” *Coastal and Estuarine Studies,* American Geophysical Union, Quantitative Skill Assessment for Coastal Ocean Models, D.R. Lynch and A.M. Davies (eds.), **48**, 153-174 (1995).

16. D.R. Lynch, J.T.C. Ip, C.E. Naimie and F.E. Werner, “Comprehensive coastal circulation model with application to the Gulf of Maine,” *Continental Shelf Research*, **16**(7), 875-906 (1996).

17. D.R. Lynch, M.J. Holboke and C.E. Naimie, “The Maine Coastal Current: spring climatological circulation,” *Continental Shelf Research*, **17**(6), 605-634 (1997).

18. D.R. Lynch, C.E. Naimie and C.G. Hannah, “Hindcasting the Georges Bank Circulation, Part 1: Detiding,” *Continental Shelf Research*, **18**, 607-639 (1998).

19. D.R. Lynch and C.E. Naimie, “Hydrographic data assimilation on Georges Bank,” M.L. Spaulding and A.F. Blumberg (eds.), *Estuarine and Coastal Modeling V*, (American Society of Civil Engineers, Reston, VA, 1998), pp. 523-540.

20. D.R. Lynch, W.C. Gentleman, D.J. McGillicuddy Jr. and C.S. Davis, “Biological/Physical Simulations of Calanus finmarchicus Population Dynamics in the Gulf of Maine,” *Mar. Ecol. Prog. Ser*, **169**, 189-210 (1998).

21. D.R. Lynch, C.V.W. Lewis and F.E. Werner, “Can Georges Bank Larval Cod Survive on a Calanoid Diet?” Special Georges Bank Issue, *Deep-Sea Research II*, in press (1999).

22. M. Mangel, “Models, physics and predictive biological oceanography: KNOW your organism,” *U.S. GLOBEC News*, **4**, 1-2 (1993).

23. C.B. Miller, D.R. Lynch, F. Carlotti, W. Gentleman and C. Lewis, “Coupling of an Individual-Based Population Dynamics Model for Stocks of Calanus finmarchicus with a Circulation Model for the Georges Bank Region,” *Fisheries Oceanography*, **7**(3/4), 219-234 (1998).

24. D.J. McGillicuddy, D.R. Lynch, A.M. Moore, W.C. Gentleman and C.S. Davis, “An Adjoint Data Assimilation Approach to the Estimation of Pseudocalanus spp. Population Dynamics in the Gulf of Maine-Georges Bank Region,” *Fisheries Oceanography*, **7**(3/4), 205-218 (1998).

25. D.J. McGillicuddy Jr., D.R. Lynch, P. Wiebe, J. Runge, W.C. Gentleman and C.S. Davis, “Evaluating the USGlobec Georges Bank Broad-Scale Sampling Pattern with Observational System Circulation Experiments,” Special Georges Bank Issue, *Deep-Sea Research II*, in press (1999).

26. C.E. Naimie, J.W. Loder and D.R. Lynch, “Seasonal variation of the 3-D residual circulation on Georges Bank,” *J. Geophysical Research*, **99**(C8), 15,967-15,989 (1994).

27. C.E. Naimie, “Georges Bank residual circulation during weak and strong stratification periods – Prognostic numerical model results,” *J. Geophysical Research*, **101**(C3), 6,469-6,486 (1996).

28. C.E. Naimie, R. Limeburner, C. Hannah and R. Beardsley, “Comparison of observed and modeled drifter trajectories in the Georges Bank region,” *Deep-Sea Research*, submitted (1999).

29. C.E. Naimie, J.W. Loder and D.R. Lynch, “Seasonal Variation of Three-Dimensional Residual Circulation on Georges Bank,” *J. Geophysical Research*, **99**(C8), 15,967-15,989 (1994).

30. C.E. Naimie, “Georges Bank bimonthly residual circulation – Prognostic numerical model results,” *Dartmouth College Numerical Methods Laboratory Report NML*, September 1995, Hanover, NH.

31. A. Okubo, “Dynamical aspects of animal grouping: swarms, schools, flocks, and herds,” *Advances in Biophysics*, **22**, 1-94 (1986).

32. D.J. Thompson, “Criteria for the selection of stochastic models of particle trajectories in turbulent flows,” *J. Fluid Mechanics*, **180**, 529-556 (1987).

33. F.E. Werner, F.H. Page, D.R. Lynch, J.W. Loder, R.G. Lough, R.I. Perry, D.A. Greenberg and M.M. Sinclair, “Influences of mean advection and simple behavior on the distribution of cod and haddock early life stages on Georges Bank,” *Fisheries Oceanography*, **2**(2), 43-64 (1993).

34. F.E. Werner, R.I. Perry, R.G. Lough and C.E. Naimie, “Trophodynamic and advective influences on Georges Bank larval cod and haddock,” Special Volume on Georges Bank, *Deep-Sea Research II*, **43**(7-8), 1,793-1,822 (1996).

35. R.A. Luettich and J.J. Westerink, “Continental shelf scale convergence studies with a barotrophic tidal model,” *Quantitative Skill Assessment for Coastal Ocean Models, Coastal and Estuarine Studies,* American Geophysical Union, D.R. Lynch and A.M. Davies (eds.), **48**, 349-371 (1995).

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Where the Waves Are

Predicting the weather is hard enough. Predicting waves is maddeningly difficult—it makes weather forecasting look like something that could be done by, well, those people on the television news who split their time between cold fronts, chatting with the sports anchor, and sending out birthday greetings to centenarians.

One of the big problems is collecting data. Waves are greatly influenced by local conditions, and ocean scientists rarely have the degree of data granularity they would need to forecast waves even for relatively small coastal regions. When it comes to the open ocean or larger coastal areas, you can almost forget about it—sampling buoys are expensive, short-ranged, and in relatively short supply. Observation from space is promising, but even with new, sophisticated satellites it's difficult to balance the necessarily high level of detail with the equally necessary timeliness and extent of coverage.

In the following article, Vincent and Jensen describe how advanced modeling techniques can fill in the data gaps and give ocean scientists powerful new tools for wave forecasting and nowcasting.

- J.P.

Improving Wind Wave Prediction on the Ocean

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Introduction

Every sailor who has ventured onto the open ocean and every Marine and SEAL who has worked on a beach knows the power of wind generated ocean waves (Figure 1). Major storms produce individual waves that can exceed 30 m in height. Naval and maritime history are replete with accounts of ships lost and battles affected by these whims of nature. Today, Naval operations are not only affected by such large waves, but by waves that are tame by the mariner's ordinary standards. Littoral operations near beaches (such as those required by Joint Logistics Over the Shore Operations) can be severely affected by waves as low as sea-state 3 (1-2 m waves). Other Naval operations can be affected by relatively low waves of an inconvenient period that cause resonance or relative motions between vessels.

Fig. 1 – Large wave with very long crest. The flat trough just before this wave will feel like a hole the ship falls into.

Ocean waves are difficult to measure or to predict accurately for two fundamental reasons. First, wind waves are the most dramatic and obvious issue of the coupling of the atmosphere and ocean. Poor prediction of the wind stress over the ocean leaves small hope of estimating the waves accurately. Waves evolve as an integration of the wind stress over time and space in complex, imperfectly understood ways. Moreover the feedback between the growing waves, the atmosphere, and the ocean's mean circulation is not yet understood in detail. Waves can grow rapidly over short times and distances. For example, a tropical storm (winds less than 30 m/sec) may grow into a category 4 hurricane (winds greater than 65 m/sec) in one day, with the waves rising from 4 to 15 meters in height, and may remain relatively localized. In such a storm the region of very high waves may cover a region only 100 km in diameter.

Second, waves are dispersive: the energy injected into the ocean at one place radiates across the ocean. Waves generated in the Indian Ocean, for example, can produce high surf on the California coast. Swells with twenty-second periods from the Halloween Nor'Easter of 1991 (located off New England) pounded the coast of Florida nearly 2,000 km away.

Ocean currents and bathymetry can influence wave propagation (Figure 2). If the bathymetry is known, its effect can be estimated, but the effects of ocean currents are rarely considered. The effects of bathymetry or currents on the wave field can be dramatic over short distances, with important variations occurring

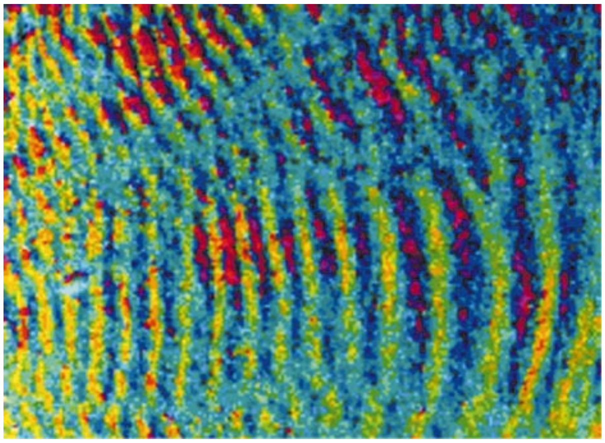


Fig. 2 – Wave Field In the Entrance of San Francisco Bay. Here the surface current speed due to the waves is mapped in color: darker blues are troughs, greens to reds are crests. The wave field is affected both by the water depth and the outflow from the bay. The image covers about 1 by 1.5 km.

over distances shorter than a kilometer, especially in very shallow water.

Given such variability in time and space, observation or monitoring programs based on *in-situ* instrumentation are not practical on a global basis. Satellite oceanography is beginning to provide additional information but it remains inadequate for addressing routine operational needs. Today (and for the foreseeable future) most analyses ("nowcasts") and forecasts remain based on numerical prediction models driven by numerical *weather* prediction models. *Indeed much of the recent improvement in wave prediction has come from advances in weather prediction.*

These models must now be run at large weather prediction centers with major computing power. However as the speed of computers increases and the distribution of information via web-based technologies advances, many practical wave models may be run in ships—or even on laptops on the beach.

In this article we review the current state of the art in wave modeling at a number of spatial scales and outline research efforts underway to improve wave prediction. We discuss two types of models: phase-averaged (spectral) models and phase-resolving models. Phase-averaged models predict the statistical composition of the sea surface. Phase-resolving model individual waves. Development of site specific coastal models that can be coupled to in-situ or locally remote sensed data collection systems offer significant opportunities for improving wave estimates for Naval operations.

Representing Ocean Waves

Intuitively we describe the sea's roughness in terms of wave height. The traditional definition of roughness uses a statistical index called the "significant wave height."

Significant wave height is defined as the average of the highest third of the waves measured in an observing period of, typically, 5-40 minutes. This rather odd definition arose during World War II to reflect and quantify observers' visual estimates of wave height. The advent of modern measurement technology lets us relate this to several more statistically relevant measures of either the variance of the poŸ…tion of the sea surface or the probability of distribution of individual waves. In the deep ocean if the significant height has a value H_s, the maximum wave that expected is less than $2.0H_s$ and the average wave height is about $0.6H_s$. Other parameters of interest are a characteristic period (or frequency) and wave travel direction.

The sea surface usually forms out of a complicated mixture of waves from different sources. Waves generated by local winds (sea), and waves from several distant sources (swell) all contribute. Each of these systems has a characteristic height, period and propagation direction. Thus the commonly used significant wave height (with period and direction) rarely describe the sea state well, other than as a general index of its severity.

Modern wave measurement and prediction technology is based on the concept of the directional spectrum of the sea surface. The sea surface over some small finite spatial region is a wavy surface with periods ranging from 0.5 second to 25 seconds. The directional spectrum of the ocean is generally represented as a polar contour plot (Figure 3) of energy density versus frequency and direction (f,θ). It is either

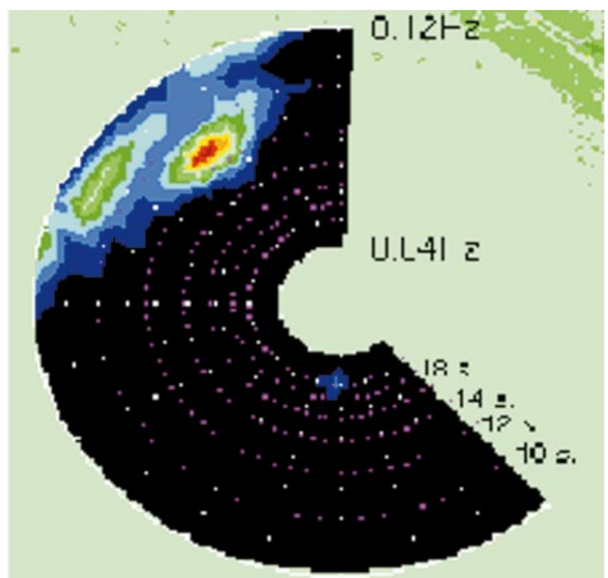


Fig. 3 – Directional spectrum measured off Pt. Reyes, California. Non-black color intensity denotes energy level as a function of frequency (radially out from center) and direction. Here we see the largest waves at about 14 s from the northwest, with a higher frequency wave train, perhaps sea, at 9 s from the WNW. There is some hint of a small swell from the Southern Ocean from the S at 18s.

computed from the Fourier transform of some parameter of the sea surface or estimated by a wave model. Examinating the spectrum allows us to identify and track the energy level, period-range and direction of movement of different wave systems. because the directional spectrum is a statistical distillation of information about the sea surface, it is neither a complete nor a unique description of that surface. For this we need to add the phase relationships of all the waves. Most operational wave models predict the spectral characteristics of the sea surface in which the phase information has been averaged and lost. Newer, more complicated models that calculate the phases of waves are under development. While phase-averaged spectra typify ocean conditions over minutes or hours, phase-resolving models are valid over a few minutes at best.

Measuring Waves

The Navy would like maps or databases in which the sea state is displayed as a function of several forecast time periods, or in which the wave climate has been summarized. Given the temporal and spatial variation of wave systems, a resolution of 1 degree by 1 degree may be barely adequate on a global scale—recall that the eye of a major tropical cyclone can easily fit within such a box. For coastal applications where the waves may be greatly affected by bathymetry, a kilometer by kilometer square may be inadequate. Yet measurements of the wave field at either of these resolutions is not available on a routine basis, largely due to cost.

The advance of signal processing and electronics technology since World War II has permitted development of a number of different gauges or buoys for making wave measurements. In the 1950's few gauges existed around the world, and all data were gathered by hand and recorded on strip charts. Today's newer instruments may contain data chips on board that collect the raw signals and then either process and store them or telemeter them to databases. But there remain fewer than fifty buoys maintained in relatively deep water with data available for use in global wave analyses, and most of those are located near the US and European coasts. While of great local value, they do not provide a robust sampling of the wave field on most days. Small ship-deployable systems exist, and these are useful for local purposes, but they remain expensive.

Contrast the state of wave prediction with the much happier condition of weather prediction. Satelites that can sample some meteorological parameters almost continuously have remarkably advanced the state of the weather prediction art. Now, ocean waves can be observed from space, but the present set of sensors—altimeters and synthetic aperture radar (SAR)—must be flown in low earth orbits. These instruments can therefore measure or infer continuous, narrow great circles of wave information, but the low orbital tracks only permit them to sample apart of the ocean in any day (Figure 4). Furthermore, the satelites usually repeat their tracks only every 17 and 34 days. So the waves at any fixed location are sampled only a couple of times a month. In the long run these data will build a wave climatology, but they are of limited usefulness in making even a daily map of wave conditions. The satellite data are, however, valuable in data assimilation schemes by helping constrain the computations in wave models driven with wind stress.

In the 1950's pioneering work by Willard Pierson—who noted that ocean waves could be represented spectrally—and by Owen Phillips and John Miles—who developed source terms that represented the input of energy from the air to the sea— ushered in the modern era of wave modeling technology. Research by Klaus Hasselmann established the role of nonlinear wave interactions in spectral evolution and so further advanced the development of wave models. With these theories and techniques, the spectral characteristics of the sea surface can be estimated in detail from global numerical wind products. The Navy's Fleet Numeric Meteorology and Oceanography Center (FNMOC) was a pioneer in applying these models. Today several centers like

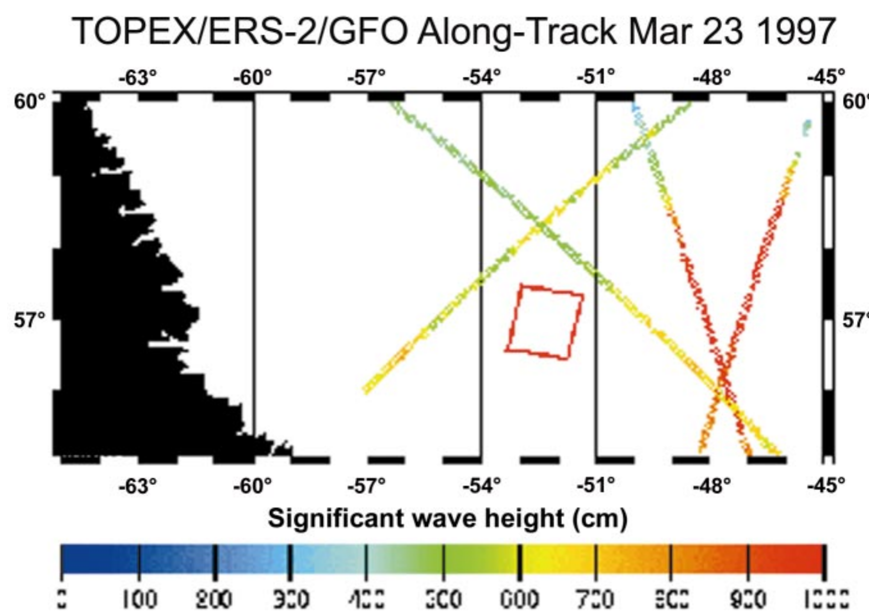


Fig. 4 – Satellite data off of Canadian Atlantic Coast March 3, 1997. The red box is the area with an ERS-2 SAR image. The colored great circles are all the nearby altimeter passes for the day color coded by wave height. The SAR image does not tell wave height directly. The altimeters suggest that the waves were somewhere between 5 and 10 m in height. To estimate wave heights off the track, one must interpolate on model.

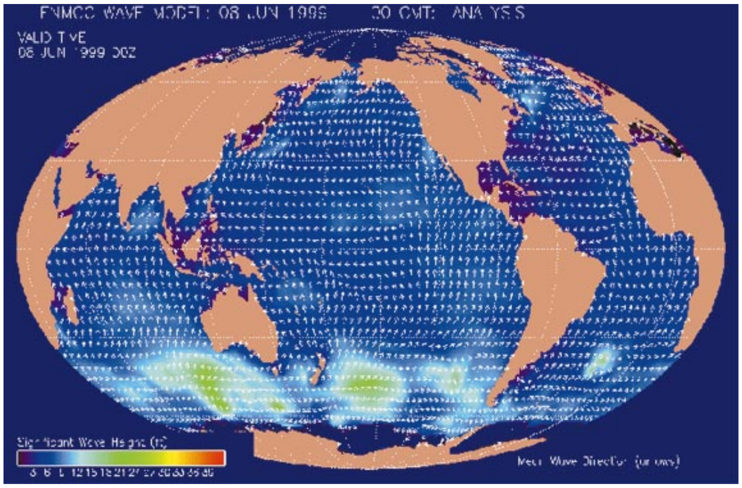


Fig. 5 – FNMOC Global WAM Run for June 8, 1999 00Z. Largest waves (7 - 8 m) are in the southern hemisphere where it is

the National Center for Environmental Prediction (NCEP), the European Center for Weather Prediction (ECMWF), the Atmospheric Environment Services (AES) in Canada, and the British Meteorology Office (BMO) routinely produce global forecasts. The Naval Oceanographic Office (NAVO) at the Stennis Space Center in Mississippi also makes a global forecast it uses to initialize smaller regional models. The computer requirements for these models (at a 1 or 2 degree resolution) are no longer as formidable as they once were (Figure 5).

At present the state of the art in wave models is generally thought to be the WAM model (1). This model is run at FNMOC, NAVO, NCEP, ECMWF, and AES-Canada, with differences in geographical gridand spectral resolution. The most significant differences in the wave forecast products are due to the wind stress products used to drive the models. WAM was developed in the mid-1980's and came into wide use in the 1990's.

Komen *et al*.(1) provides a comprehensive review of the physics and numerical approximations used in the WAM wave model. The radiative transfer equation provides the WAM's general basis:

$$DE(f,\theta)/Dt = S_{in} + S_{nl4} + S_{ds} \qquad (1)$$

In which the left side accounts for the propagation of wave energy and the right side represents the input of energy from the atmosphere (S_{in}), dissipation due breaking (S_{ds}), and redistribution of energy within the spectrum by nonlinear wave resonance (S_{nl4}). Komen *et al*. (1) provides details of the computation of each. The basic theory of wind wave generation holds that:

(a) pressure fluctuations due to the turbulent wind field build small steep waves which

(b) then are enahnced by modifying air flow over the waves that

(c) interact with each other through third-order four wave resonant originally described by Hasselmann (2) shifting energy to longer waves, and

(d) with dissipation due to white capping occurring as individual waves become too steep.

The WAM model is often called a third-generation model because it attempts to estimate the four-wave resonance directly and does not constraint the frequency spectrum to a pre-determined form as did two earlier generations of wave models. Recently, Tolman *et al*. (3) revised the WAM model and produced alternate formulations of the source terms. This model is run at NCEP.

Improvement of wave models was hampered by the quality of the wind fields used to drive the models. So little wave gauge data and insufficient certainty in the meteorology usually made it possible to make reasonable adjustments to the wind field analyses to force the wave model results into acceptable agreement with the measurements. But this only works where you have data. Advances in meteorological data collection and modeling have now greatly improved wind forecasts. Coupling these with more wave data allows a more rigorous evaluation of the wave models and allows weaknesses in the theories and models to be pinpointed (4). Over the last ten to fifteen years the RMS errors and biases for FNMOC wind wave predictions have been significantly reduced (Table 1). In research studies where time is available to refine the wind analyses, wave model predictions accurately reproduce what is measured (Figure 6).

Evaluation of the wind wave prediction system suggests systematic errors in the wave model. In very large storms (when the wind fields are well reproduced) the model under-predicts wave height and period. Often swell periods are a few seconds too short, and the model does not yield the

Table 1 – Changes in Wave Height Prediction Accuracy at FNMOC.

	SOWN 1985 a	GSOWM 1985 a	GWAM 1995 b	GWAM 1995-97 c
RMS Error	0.83-2.76m	0.73-1.86m	0.75-0.78	0.51
Bias	x	x	-.17-+0.20	+0.02
Scatter Index	0.40-0.59	0.28-0.40	0.22-0.28	0.21

Note: Column (a) Reference (5), (b) Reference (6); (c) Reference (7). Only (c) is based on a large sample from many locations. The scatter index is the ratio of the RMS error to the mean value and provides an index of relative error.

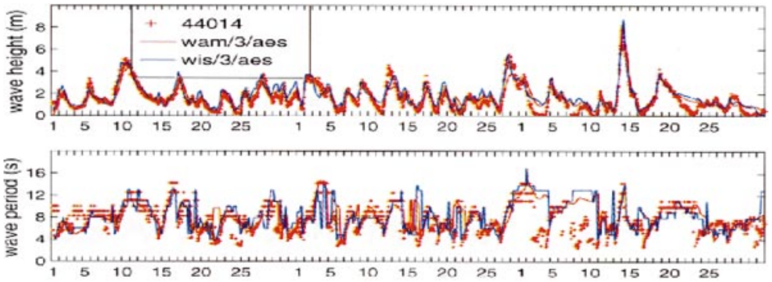


Fig. 6 – Waves of January-March 1993 using hindcast winds and WAM and a second-generation model. Data from NDBC buoy 44014 off North Carolina.

range of temporal variation in swell energy even though the mean value is about right. Analyses of hurricane data indicate poorer performance on the left side of the storm (relative to the direction of its motion) and when the storm stalls, or loops. For many years wave researchers have felt that wave directions would tend not be as well predicted as heights or periods, but recent evaluation of Naval predictions suggest that the wave arrival directions are often well predicted.

Research is beginning to offer clues to possible causes for some errors. Resio *et al*. (8) has suggested that under-prediction in big storms is due to how the Pierson-Moskowitz spectrum has been parameterized for large winds. The proposed new form allows larger and longer waves to develop in big storms. Since long swell originates in big storms, this may help alleviate the under-prediction of swell periods. The new model of Tolman *et al*. (3) at NCEP has an improved numerical scheme for wave propagation. Even without the improved fully developed formulation this model reproduces the range of variation in swell energy better than the Navy WAM model. Improving the model in tropical storms is difficult because of the lack of a good wind and wave database. So we cannot partition the error into meteorological and wave model parts.

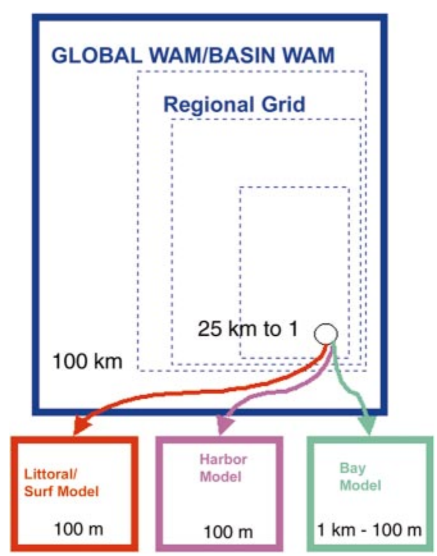
Regional And Coastal Spectral Models

People now routinely run global spectral models on about a one-degree grid mesh. Compared to the first "global" models run on about a 3-degree grid mesh, and mainly over the northern hemisphere alone, resolution has increased by almost an order of magnitude in grid computation points. Even at this scale, however, the model cannot resolve tropical storms or frontal passages, or define sheltering effects due to islands and continental landmass configuration. Nor can these models represent mesoscale features in the wind fields. A one-degree resolution is normally inadequate to represent variations in the wave field due to bottom bathymetry irregularity if the water is shallow. The current strategy uses a sequence of nested grids that refines the model resolution to the areas where it is needed (Figure 7). For example, near the Atlantic coast of the United States a series of nested grids brings the model down to a 1 km spacing (Figure 8). Even though the most sophisticated operational wind models like the Navy's Coupled Ocean/Atmospheric Mesoscale Prediction System (9) are not run on this fine a resolution, this grid is needed to represent gradients in the wave field due to changes in water depths. If the bathymetry is particularly complex, even finer resolutions are needed to represent its effects on wave propagation and breaking. For selected operational purposes even higher grid resolutions can be run. In the research model, wave models are being evaluated down to 100-meter grid resolutions that even include the surf zone. Naval prediction systems now have the capability to take the waves into harbors and bays as well.

Although the WAM model includes some aspects of shallow water wave physics, it remains inadequate for true coastal applications on sub-one-kilometer grid meshes. Research currently sponsored by the Office of Naval Research aims at improving our understanding of the physics of WAM-type spectral models for shallow water. This research program includes a major field experiment, the Shoaling Waves Experiment (SHOWEX) off of the North Carolina coast scheduled for the fall of 1999 to measure the source terms that are appropriate extensions to equation (1) for shallow water. More information on SHOWEX can be found on the SHOWEX web page: http://cheyenne.rsmas.miami.edu/duck99/.

The Office of Naval Research is sponsoring concurrent research to enhance practical aspects of shallow water wave models through the Advanced Wave Prediction Program. This effort will improve modeling of swell propagation over irregular bathymetry and allow the assimilation of both *in-situ* and remotely sensed wave data. Research has shown that injection of on site wave data often improves wave estimates locally, helping thereby to remove some of the errors inherent in trying to force a model with wind fields. A

Fig. 7 – Model Nesting Schemes. Global Nested Regional Grids, and Bay are WAM-type models. Littoral/ Surf can be either phase averaged or resolving models. Harbor Models are usually phase resolving.



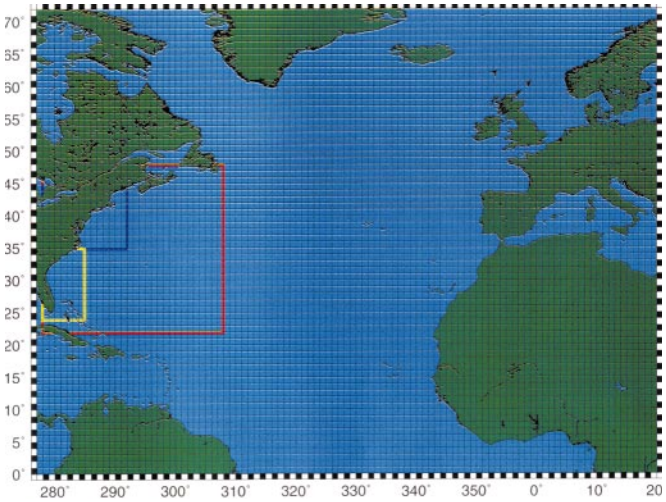


Fig. 8 – Grid Nesting for the North Atlantic.

variation of a WAM type model developed in the Netherlands and called SWAN (10) serves as the basis for improvement. SWAN has been made available to the general research community for use and evaluation so that it will be tested in a wider variety of coastal environments. More information on SWAN can be found on the SWAN web page http://swan.ct.tudelft.nl/. Updates on the Advanced Wave Prediction Program are posted on its web page: http://www.onr.navy.mil/sci_tech/ocean/Info/cd99/advwvprd.htm .

Figure 9 demonstrates some of the capabilities of SWAN by showing computations of the wave height field near San Miguel Island in California. The Naval Research Laboratory at Stennis Space Center performed these using the original version of SWAN. The model is run on a 100 m resolution and suggests that the bathymetry focuses wave energy more sharply than the old model anticipated. The challenge now lies in validating a model with such high resolution. The potential value to the Navy would be a newfound ability to pinpoint areas where littoral operations would or would not be possible.

Phase Resolving Models

The WAM, SWAN and new NCEP models are all phase-averaged spectral models. They predict the directional spectrum of the sea surface and thus permit estimation of significant wave height, period and direction of travel. Their great advantage has been the development of wind-wave generation algorithms driven by wind stress predicted by meteorological models. They do not, however, tell us much about the characteristics of *individual* waves, and yet very large, unexpected individual waves often cause great damage to ships, installations, and offshore platforms.

Information on extreme wave characteristics and wave groups must be inferred; it cannot be calculated. In shallow water important aspects of the interaction of the incoming waves with the wave generated current field and surf beat cannot presently be calculated using purely phased averaged physics. Research is underway to investigate whether phase resolving models that predict both the amplitude and phase of the waves offer more promise.

One place that phase resolution may be very useful in deep water is in predicting the appearance of rogue waves in the open ocean. Phase resolving models (11), are being evaluated under the Office of Naval Research's Mobile Offshore Base (MOB) program to see if the occurrence of unusually high, long crested waves that might occur during a big storm can be predicted. Such waves are of interest in the design specifications for a MOB, conceived as a mile long floating structure that can move from one operational area to another. Phase resolving models suggest that these rogue waves may arise out of nonlinear wave effects in an otherwise random sea. Last year in hurricane Bonnie NASA measured a wave 50 feet high with a crest about a mile long using an airborne Scanning Radar Altimeter in conjunction with the MOB program. Such a wave would look something like Figure 1 to a hapless ship in a storm. Conventional wisdom had suggested that this wave would only have a crest about 3,000 ft long.

Naval operations on beaches are affected by breaker heights, swash incursion on the beach, and nearshore currents. Models like SWAN can be applied to predict waves on the space scales of the surf zone (with a resolution of 100 meters or less). Tests of these models suggest that on many beaches these models can predict both the wave height and many aspects of the directional spectrum. But applying wave models to drive nearshore circulation models on barred beaches has been less successful than investigators had hoped.

Figure 10 shows phase resolving model simulations of a

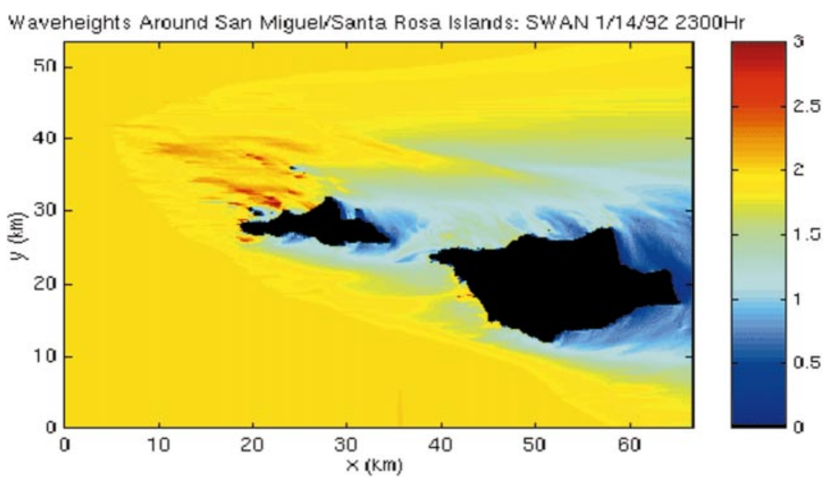


Fig. 9 – High Resolution Wave Predictions Using SWAN.

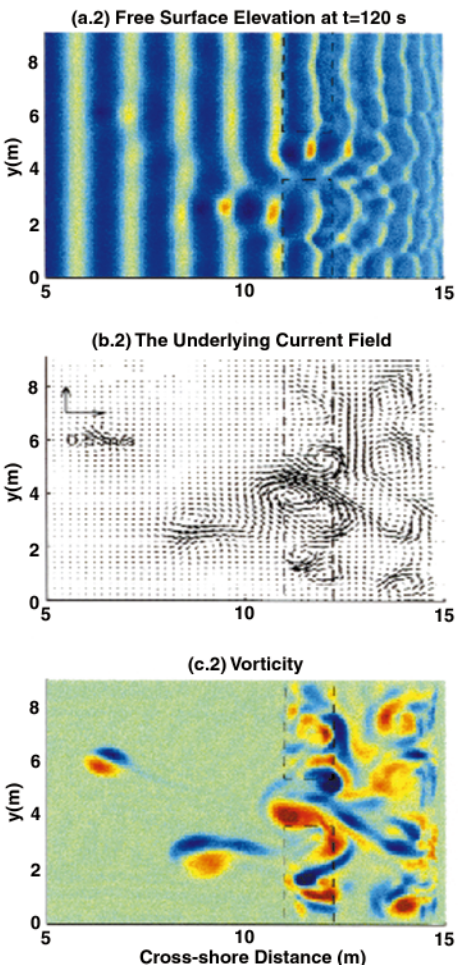


Fig. 10 – Phase resolving model simulation of a bared beach showing the wave field, the current field, and the vorticity field. The vorticity patterns show eddy-like structures that can be seen in field imagery.

simple swell interacting with a shore and a bar having a rip current channel. The simulations were made with a Boussinesq wave model of the nearshore developed at the University of Delaware (12). The Delaware model has the ability to predict nearshore waves and currents simultaneously. Although the input wave field is steady, the wave-driven nearshore current develops a rip current in the bar gap that is not steady, but pulsates in both time and position, shedding eddies. These results are in general agreement with the patterns observed in the laboratory and field (Figure 11). The key to reproducing these effects is the model's ability to transfer energy to sub- and super-harmonics of the incident wave field and allow shear instabilities in the nearshore current field to develop and interact with the incoming wave field. Phase-averaged models do not at this point incorporate the physics required to replicate these processes.

Although phase-resolving models appear to offer significant new insights into wave predictions, they are no panacea. First of all, they are incredibly computationally intensive. Even in a research mode it is impractical to run them for more than a few square kilometers. Secondly, they must either be initiated with phase information about the wave field (which cannot be inferred but must be measured) or the phase field must be simulated using statistical techniques (which then require many realizations to obtain statistical stability). Thus their potential for the near term may lie in improving our understanding of the physics to allow development of better phase averaged models.

Summary

Over the past decade advances in computers and electronics, in satellite meteorology and oceanography, and in numerical weather prediction have allowed development of practical ocean phase averaged spectral wave models. These models are now run on temporal and spatial scales appropriate to the available wind forcing information and bathymetry. Phase resolving models are under development that allow highly detailed simulations of the ocean surface, and the interaction of waves with bars, beaches and currents. Now that the forcing wind data are better known, research is underway to identify and correct deficiencies in the wave models.

Challenges for the near future remain validation of the details of the model's predictions, and coupling wave observation systems to the models to permit application of data assimilation techniques. Users and developers of the models must work to find better ways of representing and interpreting the wealth of information these models produce. For the longer term, our goal is to improve the models so that they used coupled physics to describe the interaction of the waves and ocean, and waves and atmosphere in a physically realistic manner.

Fig. 11 – Photograph of swell breaking on a beach and generating a rip current near La Jolla, CA. (Elgar)

Acknowledgments

The figures for this article were obtained from the following sources and are gratefully acknowledged: Figure (2), Richard Goldstein of the Jet Propulsion Laboratory, California Institute of Technology; (3) Website of the California Coastal Data Information Program; (4) David Walker, ERIM International; (5) Website of the Fleet Numerical Oceanography and Meteorology Center; (9) James Kaihatu, Naval Research Laboratory; (10) Professor James Kirby, University of Delaware; (11) Dr. Steve Elgar, Woods Hole Oceanographic Institute.

References

1. G. Komen, L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann and P. Janssen, *Dynamics and Modeling of Ocean Waves* (Cambridge University Press, 1994), p. 532.

2. K. Hasselmann, "On the Non-Linear Energy Transfer in a Gravity-Wave Spectrum – General Theory," *J. Fluid Mechanics*, **12**, 481-500 (1962).

3. H. Tolman and D. Chalnikov, "Source Terms in a Third Generation Wind Wave Model," *J. of Physical Oceanography*, **26**, 2,497-2,518 (1996).

4. V. Cardone et al, "Evaluation of Contemporary Ocean Wave Models in Rare Extreme Events: The 'Halloween Storm' of October 1991 and the 'Storm of the Century' of March 1993," *J. of Atmospheric and Oceanographic Technology*, **13**, 198-230 (1996).

5. M. Clancy et al, "The Fleet Numerical Oceanography Center Global Spectral Ocean Wave Model," *Bulletin of the American Meteorology Society*, **67**(5), 498-512 (1986).

6. P. Wittmann, M. Clancy and T. Mettlach, "Operational Wave Forecasting at Fleet Numerical Meteorological and Oceanography Center," *4th International Workshop on Wave Hindcasting*, Banff, Alberta, Canada, (Atmospheric Environment Service, Downsview, Ontario, Canada, 1995), pp. 335-342.

7. J. Bidlot, M. Holt, P. Wittmann, R. Lalbeharry and H. Chen, "Towards a systematic verification of operational wave models," *Waves '97, Ocean Wave Measurements Analysis*, American Society of Civil Engineers, 653-667 (1997).

8. D. Resio et al, "Wind Speed Scaling in Fully Developed Seas," *J. of Physical Oceanography*, accepted for publication (1999).

9. R. Hodur, "The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Predication System (COAMPS)," *Monthly Weather Review* (1996).

10. N. Booij, L.H. Holthuijsen and R.C. Ris, "The SWAN wave model for shallow water," *Proceedings, 25th International Conference on Coastal Engineering*, **1**, 668-676 (1996).

11. D. Dommermuth and D. Yue, "A Higher Order Spectral Method for the Study of Nonlinear Gravity Waves," *J. of Fluid Mechanics*, **184**, 267-288 (1987).

12. Q. Chen et al, "Boussinesq Modeling of a Rip Current System," *J. of Geophysical Research*, accepted for publication (1999).

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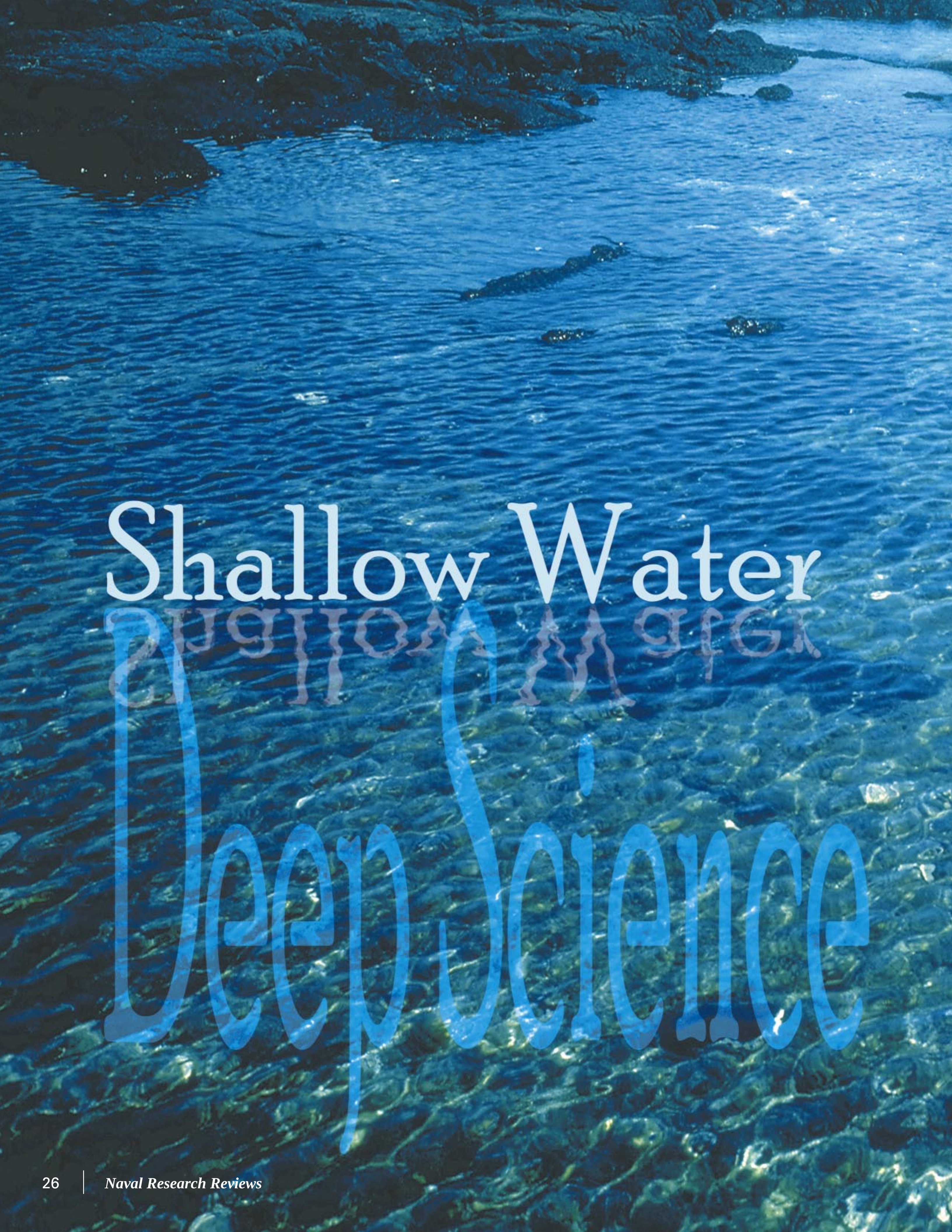
Shallow Water Deep Science



The Navy has long been interested in ocean forecasting as a way to anticipate the ocean's influence on naval operations both under and over the sea. In the past, most of the research focused on deep-water environments where ships and submarines carried out their missions. Shallow coastal waters of the world present an added challenge as the focus of future naval operations will likely be in these littoral, or near-shore, areas. In the littoral zone, Navy oceanographers are studying a cat's cradle of challenges: tidal pulses, beach profiles, reefs, bars, shallows, shoals, channels, sediment transport, turbidity, rain rates, river run-off, biological components and the complex weather patterns inherent in any coastal region.

Today's oceanographers study the littoral zone the same way they study deep water—through sampling. Although the methodology is traditional, the tools of the trade now include satellite and remote-sensing technologies and sophisticated ocean-modeling software.

With advances in technology, oceanographers can increasingly provide the Navy with data collection, analysis and recommendations in near real time. In the old days, studies took weeks—even months—to return enough data for analysis. Today, most sampling systems, including the HOPS and LEO-15 versions mentioned in the article that follows, incorporate both observation and modeling techniques to maximize the benefits of both capabilities. The systems gather data on an ongoing basis from autonomous platforms, allowing the researchers to adapt sampling patterns as needed to generate useful forecast models. In a continuous feedback loop, adaptation of future sampling is based on model simulation results. *- D.B.*

Adaptive Sampling for Ocean Forecasting

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Abstract

Real-time regional forecasting of the coastal ocean is a challenging task, complicated by the ocean's episodic nature, the lack of extensive observations, and the combined influence of internal processes and interactions with boundaries on the evolution of the forecast fields. Adaptive sampling is an evolving methodology for the efficient sampling of ocean phenomena in support of real-time nowcasting and forecasting activities. Ocean Observation and Prediction Systems (OOPS) provide a framework for acquiring, processing and assimiliating data in a dynamical forecast model which can then generate forecasts of 3-D fields and error estimates that can be used to optimize adaptive sampling schemes for specific goals. Modern OOPS applications with adaptive sampling are presented for the Harvard Ocean Prediction System (HOPS) and the Rutgers University Long-term Ecosystem Observatory (LEO-15). Interdisciplinary models, new assimilation methodologies, new sensors, autonomous platforms, and automated system responses will further improve adaptive sampling capabilities in the next decade.

Real-Time Regional Forecasting

The ocean is intermittent, eventful, and episodic. It is an essentially turbulent fluid whose circulation is characterized by a myriad of dynamical processes occurring over a vast range of nonlinearly interactive scales in space and time. Ocean forecasting is essential for effective and efficient operations on and within the sea, and such forecasting has been initiated, e.g. for military operations, coastal zone management and scientific research. Observations are used to initialize dynamical forecast models, and further observations are continually assimilated into the models as the forecasts advance in time. Such observations are generally difficult, costly and sparse. If a region of the ocean were to be sampled uniformly over a predetermined space-time grid adequate to resolve scales of interest, only a small subset of those observations would have significant impact on the accuracy of the forecasts. The impact subset is related to intermittent energetic synoptic dynamical events. For most of the energetic variability in the ocean, the location and timing of such events is irregular and not *a priori* known. However, a usefully accurate forecast targets such events and forms the basis for the design of a sampling scheme tailored to the ocean state to be observed. Such adaptive sampling of the observations of greatest impact is efficient and can drastically reduce the observational requirements, i.e., by one or two orders of magnitude.

The ocean evolves in time, both as a direct response to external surface and body forces, and also via internal dynamical processes. The former include, for instance, tidal forces, winds and surface fluxes of heat and fresh water. Where air-sea interactions are important, an accurate meteorological forecast is needed for the ocean forecast. Oceanic internal instabilities and resonances, which include meanders of currents, frontogenesis, eddying and wave propagation, are generally analogous to atmospheric weather phenomena and are called the internal weather of the sea. The spatial scales of important internal ocean weather phenomena are short and require ocean forecasts to be carried out regionally rather than globally. The regional forecast problem then has additional forces appearing as fluxes through horizontal boundaries, representing both larger scales of direct forcing, remote internal dynamical events and land-sea interactions in the littoral zone. The development of a regional forecast system and capability depends both upon the scales and processes of interest and the scales and processes that are dominant in the region. The design of sampling schemes is constrained both by generic and special regional issues. The forecast region or region of influence is often necessarily larger than the region of operational interest. Additional challenging issues in sampling design include efficient real-time forecast protocols and the acquisition of data adequate for both updating and verification purposes.

Ocean science and marine technology today are increasingly interdisciplinary. Fields of forecast interest include physical, acoustical, optical, biological, chemical and sedimentological state variables. Velocities, temperatures, sound speed, scattering, irradiances, plankton concentrations, chlorophyll and suspended particles are some examples. Interdisciplinary compatibility requirements constrain multi-disciplinary sampling schemes. Some variables are of direct interest while others are useful for interdisciplinary field estimation, e.g., acoustic travel times for the estimation of temperature gradients. Thus, as the scope of ocean prediction expands, the challenging adaptive sampling problem that emerges is the design of sampling schemes for the acquisition of multi-scale compatible interdisciplinary data sets based upon real-time observations and realistic forecasts. The specific purpose of the forecast which will utilize the data guides both the design of the sampling and the choice of a forecast skill metric. The adaptive sampling problem defined in the last two sentences is the topic of this paper.

Characterization of the Coastal Ocean

The short term evolution (1-5 days) of the mesoscale ocean circulation at times is controlled by nonlinear internal processes associated with the density-driven flows, especially in deeper water. As water depths decrease, forcing from the boundaries (surface, bottom, offshore, inshore, and lateral) and turbulent mixing is often of similar importance or greater (ex. Keen and Glenn, 1998).

Atmospheric momentum and buoyancy fluxes produce daily to seasonal variations in the upper mixed layer and the seasonal thermocline. Coastal upwelling/downwelling is caused by the Ekman transport, which in the deepwater limit is associated with alongshore winds and Coriolis forces, but in the often neglected shallow water limit is associated with cross-shore winds.

THERMOCLINE. The transition layer between the mixed layer at the surface and the deep water layer. The definitions of these layers are based on temperature.

EKMAN TRANSPORT. The net movement of water influenced by friction (typically the wind or bottom drag) and the rotation of the earth.

Bottom interactions on the continental shelf are complicated by the effects of surface waves that feel the bottom, and by a moveable sediment bed. Both the nonlinear wave-current interaction in the wave boundary layer, and the increased roughness due to ripple formation, act to increase the bottom stress felt by the lower-frequency currents, while suspended sediment induced stratification acts to decrease the bottom stress.

At the outer boundary, interactions with deepwater eddies and boundary currents can produce cross-shelf exchanges or along-shelf pressure gradients that force the outer-shelf. Along the coastal boundary, estuaries are a source of freshwater, producing buoyant plumes and alongshore surface jets on the inner-shelf. Entering through lateral cross-shelf boundaries, coastal-trapped, externally generated waves can propagate along the coast through a region of interest.

The observation and prediction of coastal circulation is further complicated by the presence of a continuum of wave motions of similar magnitude or greater than the boundary or internally forced currents. Surface waves, internal waves and solitons, barotopic and baroclinic tides, and inertial waves may occur simultaneously, and each may interact with the mean flow by modifying the turbulence, especially near the thermocline where the largest shears are often encountered.

We have chosen to emphasize the features, variabilities and complexities of the physical coastal ocean (Robinson and Brink, 1999) and will only briefly mention the equally, if not more important, multi- and inter-disciplinary processes. Coastal conditions support vigorous marine ecosystems and are of utmost importance for living marine resources. Primary production occurs in phytoplankton blooms in response to seasonal stratification, wind-driven and topographic upwelling, tidal-mixing and nutrient advection events. The dynamics of interactive, multi-scale physical-biological variabilities (phytoplankton and zooplankton patchiness) is currently a research topic of critical importance for both understanding and managing coastal seas. The forward and inverse acoustic propagation problems across the shelfbreak and in shallow waters involve critical bottom interactions and require careful treatment of attenuation, scattering and reverberation.

Adaptive Sampling Concept

The concept of experimental and observational sampling being well matched to the phenomena of interest is deeply rooted in modern scientific methodology. The success of Newtonian physics was based upon the rigorous requirement of subjecting dynamical hypotheses to quantitative testing by experimental facts. An iterative process has evolved, with feedbacks between theory and experimentation, which involves both agreements with pre-existing data and predictions of new measurements. Practical material and human resource constraints demand efficient measurements, an issue of particular concern in oceanography. Efficient sampling requires *a priori* knowledge of scales that may be simple (e.g. periodic) or complex (e.g. multi-scales arising from nonlinear interactions).

If scales are known for intermittent episodic phenomena, adequate uniform sampling is possible but not very efficient. Coarser sampling misses entirely or at best aliases the phenomena (MODE Group, 1978, Section 1). Finer sampling is redundant. Optimal sampling requires *a priori* estimates of the state of the ocean during the sampling interval. To carry out such observations adaptively requires flexible and efficient platforms well matched to the phenomena. Consider a scenario in which two (or more) platforms are available together with a real-time data telemetering capability. One platform provides continuous good coverage from a fixed position or predetermined track (saturated data, e.g. from a coastal CODAR or satellite altimeter). The second platform, generally costly to operate in the forecast region, provides targeted data (sparse data, e.g. from a ship, aircraft or AUV) on events identified but incompletely sampled in the real-time saturated data stream. Additionally, if a usefully reliable forecast model exists, present and future events can be identified from model nowcasts and forecasts instead of from a saturated data stream, but more powerfully in conjunction with such a data stream.

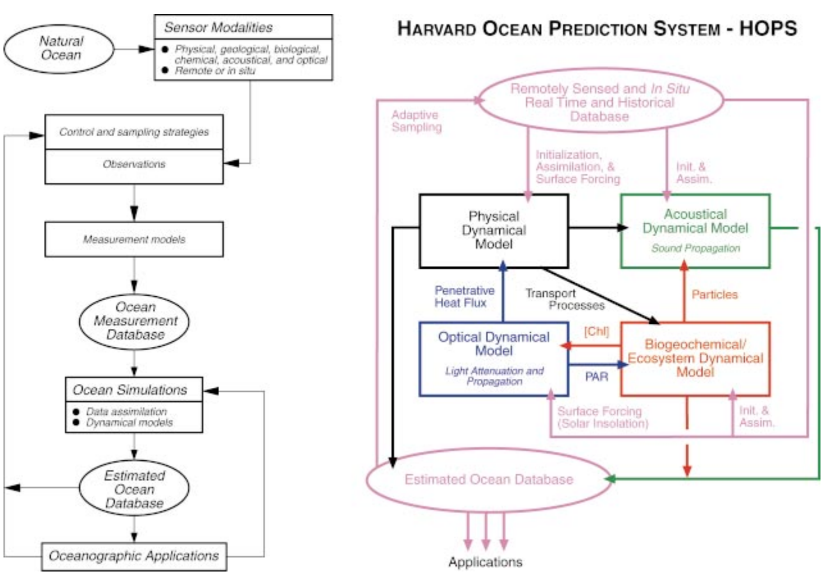
The adaptive sampling strategy will attempt to minimize a selected error measure and the estimate of the error must take into account data type, sampling and assimilation scheme. Contemporary scientific methodology is tripartite, involving theory, experimentation and realistic simulations now possible because of rapidly increasing computational resources. Observational System Simulation Experiments (OSSEs) now play an essential role in quantitatively assessing adaptive sampling strategies (Robinson *et al*., 1998).

Historically oceanographers have always adaptively sampled with respect to known scale information. Early examples include biological sampling (or harvesting) of estuarine ecosystems at appropriate phases of the tidal cycle and the design of physical time series with regard to Nyquist frequency considerations. The existence of dominant mesoscale variability in the ocean which was discovered in the 1960s, and described and quantified in the 1970s (Robinson, 1983), led naturally to the initiation of ocean forecasting during the 1980s (Mooers *et al*., 1986). During that decade the present authors independently carried out adaptive sampling research, for example in conjunction with the first real-time shipboard forecast of the California Current evolution (Robinson *et al*., 1986) and with the provision of strong ring-current advisories to dynamically positioned deep water oil drilling vessels (Glenn *et al*., 1990). Together we devised weekly event-related P3 AXBT flights in support of research/operational forecasting of Gulf Stream meanders and rings for the US Navy from November 1986 to January 1989 (Glenn and Robinson, 1995). During the 1990s the opportunities and requirements for multi-scale, interdisciplinary ocean forecasting have sharpened, the term adaptive sampling for ocean observational networks was articulated (Curtin *et al*., 1993), and the concept of Ocean Observing and Predictions Systems has firmly emerged.

ADAPTIVE SAMPLING.
Measurements whose distribution in time and space are adjusted according to observed or predicted gradients.

Ocean Observing and Prediction Systems (OOPS)

Advanced ocean observing and prediction systems (OOPS) now exist for field estimation. An OOPS consists of an observational network, data analysis and assimilation schemes and a suite of interdisciplinary dynamical models. Generally multiple interactive scales require compatible observational and modeling nests, and efficiency requires a well-chosen mix of sensors and platforms for a particular problem. The concept of advanced ocean prediction systems is represented schematically (Figure 1a) by the LOOPS (Littoral Ocean Observing and Prediction System) architecture (Patrikalakis *et al*., 1999). The LOOPS system is modular, based on a distributed information concept, providing sharable, scalable, flexible and efficient workflow and management for interdisciplinary data collection, assimilation and forecasting. The Harvard Ocean Prediction System (HOPS), described below and illustrated in Figure 1b, is at the heart of LOOPS. An OOPS can be generic and portable (e.g. HOPS (Robinson, 1999)), or designed and implemented for specific regions or processes (e.g. LEO-15 (Glenn *et al*., 1998)).



(a) (b)

Fig. 1 – a) Architecture of advanced high-level ocean observing and prediction system; b) Architecture of Harvard Ocean Prediction System (HOPS).

Data assimilation, which melds observations with dynamics, provides the only feasible basis for obtaining accurate synoptic mesoscale realizations over the space-time scales and domains of interest. Data assimilation dynamically adjusts and interpolates data inserted into models (Robinson *et al.*, 1998). Data assimilation methods being used or adapted today for ocean science have their roots in engineering and meteorology and are generally based on estimation theory, control theory or inverse techniques. Error models are an intrinsic element of data assimilation schemes and errors are propagated together with forecast fields. Data assimilation or inverse methods allow for the estimation of parameters such as eddy diffusivities and rate parameters and the inference of processes from the balance of terms in dynamical equations. The control of predictability error via data assimilation initiated by meteorologists is interesting for the interdisciplinary ocean forecasting problem in the light of the nonlinearities inherent in coupled biological and physical models.

Modern ocean observation networks use multiple platforms including remote (satellites, aircraft and shore-based), stationary (surface and subsurface), moveable (ships and AUVs), and drifting (surface or vertically mobile). The Rutgers LEO-15 system is illustrated in Figure 2 and described below. Advances in satellite, line-of-site radio, and underwater acoustic communications enable real-time data transmission, which prompts development of automated processing and visualization algorithms. Instantaneous product dissemination via the World Wide Web promotes the formation of distributed networks, with different groups responsible for individual systems. The proliferation of distributed observation networks allows one to envision a patchwork of well-sampled coastal ocean regions in which the role of sparse adaptive sampling will change relative to the role of saturated measurements. In the well-sampled ocean, adaptive sampling can begin to focus on observations that improve or otherwise compensate for imperfect model physics, such as unparameterized turbulent mixing mechanisms, as the dominant source of forecast error.

Interdisciplinary ocean science involves a hierarchy of complex coupled physical-acoustical-biogeochemical-ecosystem dynamical models. Physical models are generally primitive equation (PE) models, but small scale coastal phenomena can be represented via non-hydrostatic models. Boundary layers (top and bottom) and turbulence are modeled through process parameterization, second order closure, or large eddy simulation. Basic biological mechanisms are generally known (although not as well known as physics) but much remains to be learned about their manifestations in real ocean processes and their appropriate representation in dynamical models. Mechanisms such as nutrient uptake, grazing, mortality, etc. are highly nonlinear in nature. There are an almost unlimited number of potential state variables (species, life-stages, trophic levels, nutrients, etc.) and the choice of aggregations appropriate for particular problems (critical state variables) is a demanding aspect of modeling. Higher trophic levels of biology require behavior modeling. Acoustic propagation has a variety of approximate dynamics, depending on frequency and complicated by circulation, bottom and surface interactions, biological interactions, etc.

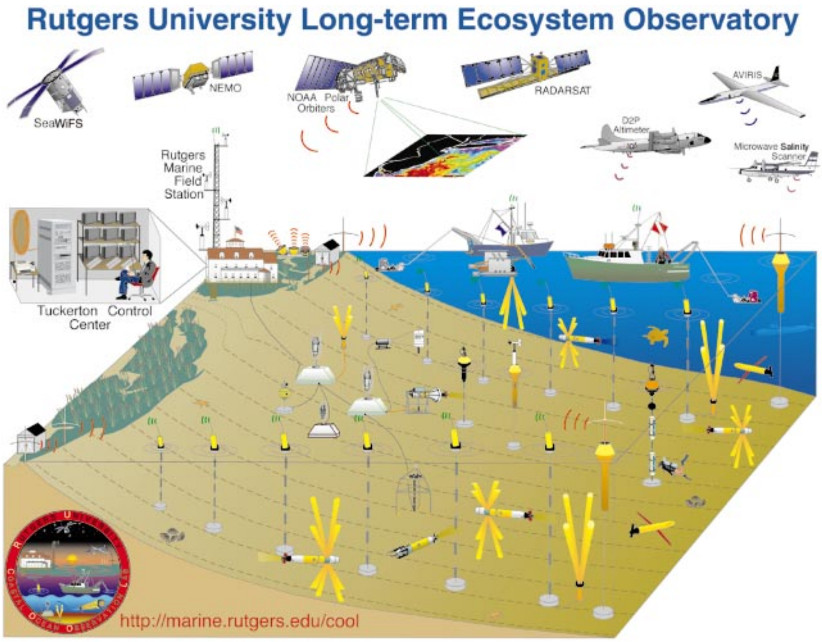


Fig. 2 – The LEO-15 observation network operated offshore of Tuckerton, New Jersey during the annual Coastal Predictive Skill Experiment.

Operational high-resolution (10-30 km) regional atmospheric models may adequately resolve most atmospheric processes, but coastal ocean fronts can occur at the kilometer scale. To determine if the smaller scale ocean features feedback on the atmosphere and influence their own evolution, an even higher resolution atmospheric model can be nested within the operational models, or a planetary boundary layer model can be coupled to each grid point of the ocean model and forced at the top with the operational resolution model. The first approach drastically increases runtime, while the second approach assumes the ocean influence is primarily local.

Research in progress and operational examples

Harvard Ocean Prediction System (HOPS): HOPS (see Figure 1b) is a flexible, portable and generic system for inter-disciplinary nowcasting, forecasting and simulations. HOPS can rapidly be deployed to any region of the world ocean, including the coastal and deep oceans and across the shelfbreak with open, partially open or closed boundaries.

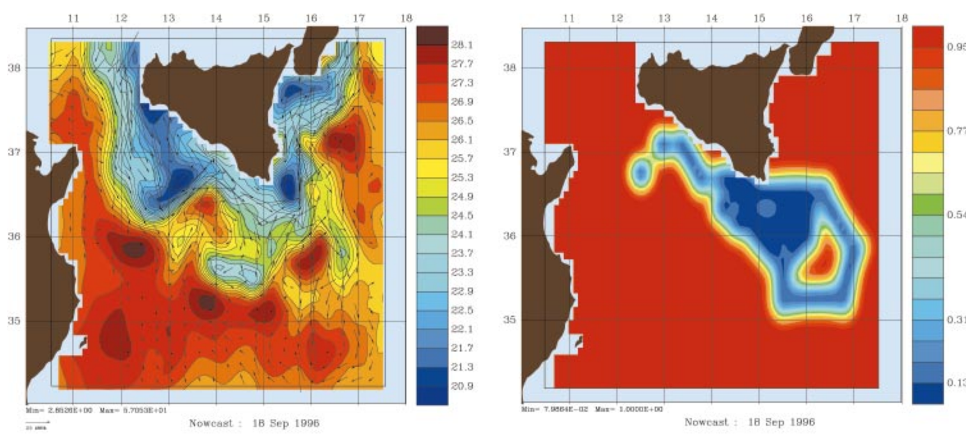
Physical, and some acoustical, real-time and at sea forecasts have been carried out for more than fifteen years at numerous sites (Robinson, 1999) and coupled at sea biological forecasts were initiated in 1997. The present system is applicable from 10m to several thousand meters and the heart of the system for most applications is a primitive equation physical dynamical model. Work is in progress to extend the system to estuaries and to include a non-hydrostatic option. Multiple sigma vertical coordinates have been calibrated for accurate modeling of steep topography. Multiple two-way nests are an existing option for the horizontal grids. The modularity of HOPS facilitates the selection of a subset of modules to form an efficient configuration for specific applications and also facilitates the addition of new or substitute modules. Data assimilation methods used by HOPS include a robust (suboptimal) optimal interpolation (OI) scheme and a quasi-optimal scheme, Error Subspace Statistical Estimation (ESSE). The ESSE method determines the nonlinear evolution of the oceanic state and its uncertainties by minimizing the most energetic errors under the constraints of the dynamical and measurement models and their errors. Measurement models relate state variables to sensor data. Real-time efficiency is achieved by reducing the error covariance to its dominant eigendecomposition.

HOPS utilizes a variety of observational networks in its applications. Satellite sea surface temperature, height and color are routinely utilized as available. HOPS, on shipboard, has recently forecast physics and acoustics from data gathered by the RV Endeavor during the ONR Shelfbreak PRIMER experiment, and physics and biology from data gathered by the RRS Discovery in the Northeast Atlantic during the Plankton Patchiness Studies by Ship and Satellite experiment. Interactive adaptive sampling with the MIT Odyssey AUVs was initiated in shallow water during the 1996 ONR Haro Straits tidal fronts experiment (Nadis, 1997). In recent NATO Rapid Response exercises, the observational networks included the SACLANTCEN NRV Alliance, additional NATO military and research vessels and P3 aircraft and ARGOS floats. A multi-scale, interdisciplinary observational network is illustrated in Figure 6 for the recent LOOPS Massachusetts Bay Sea Trial 1998.

LEO-15 Observation and Modeling System: The Rutgers University Long-term Ecosystem Observatory (LEO-15) (Grassle *et al.*, 1998) is an instrumented natural littoral laboratory that spans the 3 m to 30 m water depths offshore Tuckerton, New Jersey with a 30 km x 30 km well-sampled research space (Figure 2). This inner shelf region has “often been ignored in the past because of the very difficult operating conditions and the complex dynamics, where the water is effectively filled with turbulent boundary layers” (Brink, 1997). Real-time surface data from remote sensing platforms, combined with real-time subsurface data from remotely-operated and autonomous nodes, provide 3-D nowcasts to guide adaptive sampling with up to five coastal research vessels and a fleet of AUVs (long-range gliders, medium-range REMUS survey vehicles, and short-range REMUS turbulence vehicles) (Glenn *et al.*, 1998).

Coastal forecasts for adaptive sampling are generated using Rutgers’ Regional Ocean Modeling System (ROMS), a primitive equation model with a free sea surface, curvilinear horizontal grid, a stretched (S-coordinate) vertical grid, and open boundary conditions allowing two-way forcing between small and large scales. Turbulence closure is achieved using the KPP scheme (Large *et al.*, 1994) modified to include overlapping surface and bottom boundary layers and wave-current interactions (Styles and Glenn, 1999). Data assimilation options include nudging, optimal interpolation and a reduced-state Kalman filter. Atmospheric forcing options include operational Navy products that drive a planetary boundary layer model, or direct coupling to a high-resolution Regional Atmospheric Modeling System (RAMS).

HOPS examples: Figures 3 and 4 illustrate the use of HOPS during recent NATO Rapid Environmental Assessment (Pouliquen *et al.*, 1997) Rapid Response exercises in 1996 and 1998. A real-time nowcast for 18 Sept. 1996 is shown in Figure 3a. This nowcast is the combination of a 3-day forecast with AXBT data whose expected analysis error is shown in Figure 3b. The data-forecast melding was performed using ESSE assimilation. The sampling patterns



(a) (b)

Fig. 3 – Surface temperature map for 18 Sept. 1996 in the Strait of Sicily region overlaid with surface velocity vectors (a). The Atlantic Ionian Stream is a free jet meandering from west to east with a strong thermal front between 25-26°C.; (b) Normalized expected error (0-1) of the surface temperature mapped from the new observations.

of data collection for ships and aircraft (Sellschopp and Robinson, 1997) were subjectively adapted in real-time, combining shipboard predictions with operational needs in order to sample areas of influence for the region of interest. Figure 4a is a real-time nowcast for 21 March 1998, melding the field forecast with all the past data up to that day, via data assimilation. Figure 4b is the forecasted error standard deviation, from the ESSE assimilation scheme, of the temperature at 100m. The error field and the associated dominant eigenvectors of error covariance forecasts were utilized to design adaptive patterns of AXBT flights for the region, in accord with practical, operational and meteorological constraints.

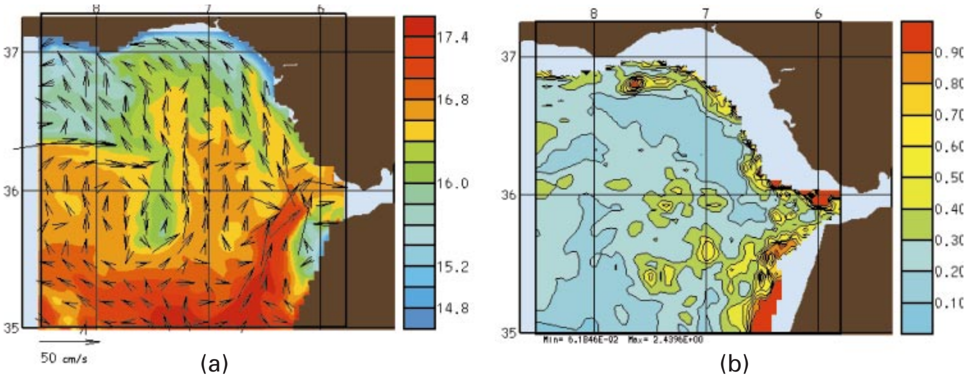


Fig. 4 – Melded estimate of temperature in the Gulf of Cadiz with velocity vectors after data assimilation for 21 March 1998 (a) and forecast error estimate

Figure 5 and Figure 6 illustrate the interdisciplinary forecast experiment that occurred for more than two months in Massachusetts Bay in late summer and early fall of 1998. This demonstration of concept real-time sea trial field experiment was performed in collaboration with the LOOPS (NOPP), Advanced Fisheries Management and Information Service (AFMIS, NASA, Rothschild *et al*., 1998) and Autonomous Ocean Sampling Network (AOSN, ONR, Curtin *et al*., 1993) programs. The scientific focus was phytoplankton and zooplankton patchiness, in particular, the spatial variability of zooplankton and its relationship to physical and phytoplankton variabilities. Simultaneous synoptic physical and biological data sets in 4 dimensions were obtained over a range of scales. This data was assimilated into HOPS using OI and ESSE. Real-time forecasts of fields and error covariance eigendecompositions were provided. These forecasts were utilized for adaptive sampling and for the calibration of the model parameters. Several dynamical interactions among the circulation, productivity and ecosystem systems were inferred.

Figure 5a shows the chlorophyll-a concentration at 10m, overlaid with horizontal velocity vectors at the same depth. Figure 5b is a cross-section of chlorophyll-a concentration along the entrance of Massachusetts Bay, from Race Point to Cape Ann. The multi-scale patchiness of the chlorophyll field is clearly visible. Higher concentrations occur at the northeast of Cape Ann and near Boston Harbor because of the continued supply of nutrients, over Stellwagen Bank due to tidal mixing, and at several locations along the coastline, because of local wind driven upwelling and episodic wind mixing.

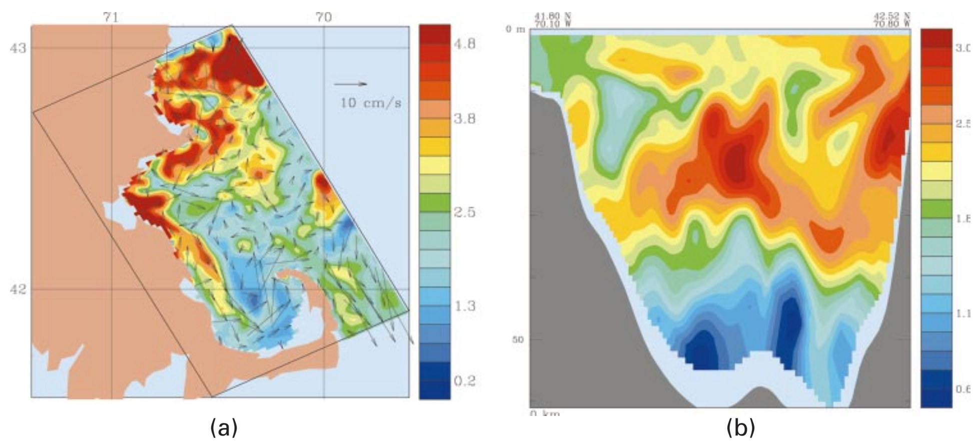
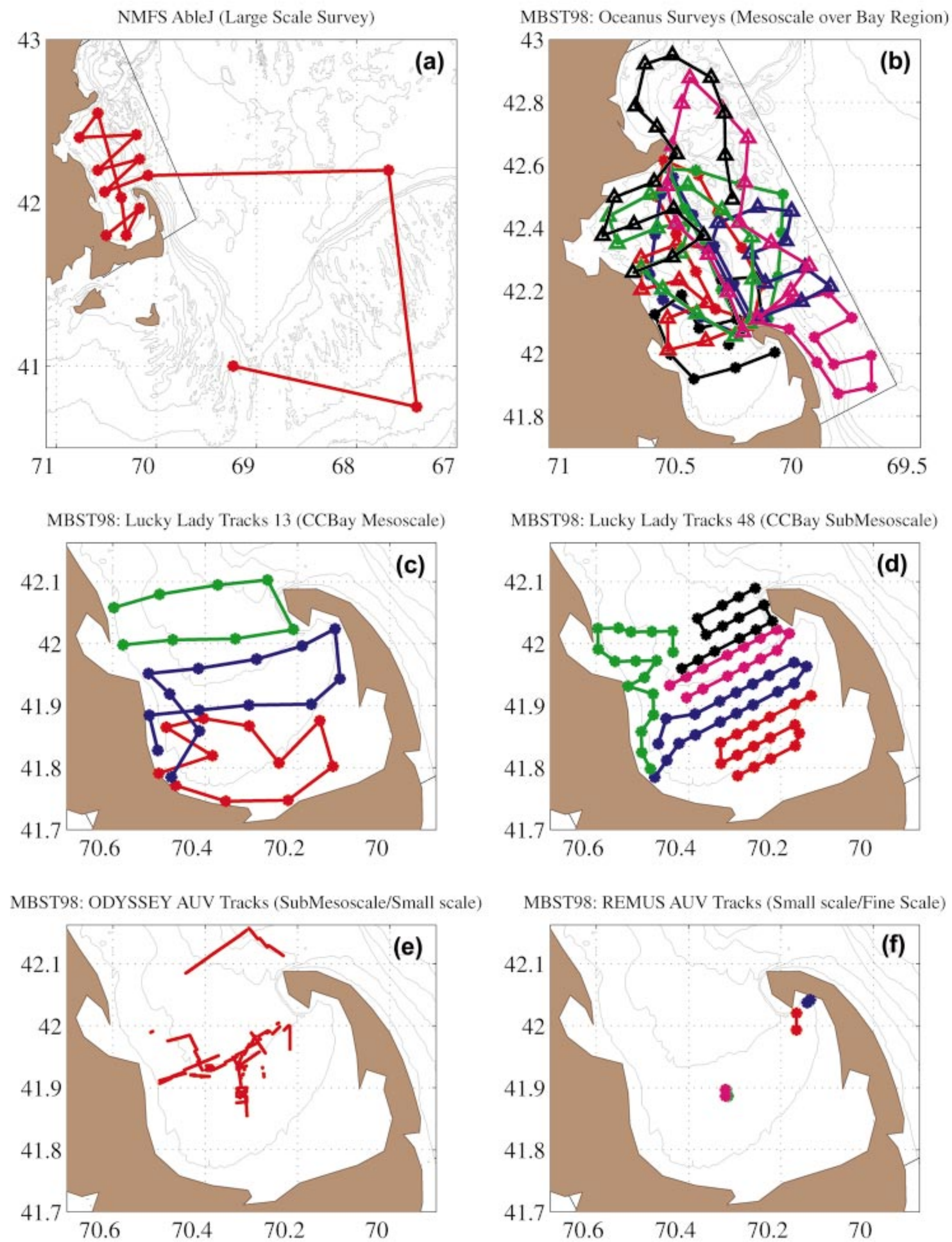


Fig. 5 – Example chlorophyll-a concentration at 10m with horizontal velocity vectors for MBST-98 (a) and vertical section of chlorophyll-a concentration from Race Point to Cape Ann (b).

Statistical error models previously developed for other ocean regions (Lermusiaux,1999) were calibrated and verified for use in Massachusetts Bay. The initial error subspace was set to the *a priori* dominant, synoptic mesoscale variability in the Bay, which is related to the dominant subspace of the so-called GFD singular vectors (Palmer *et al.*, 1998). Adaptive sampling methodologies were carried out in real-time for two months, as illustrated by Figure 6. The multi-scale sampling strategies were based on: (1) ocean field forecasts assimilating all prior data (regions of most active or interesting dynamics) and (2) forecasts of error variances and of dominant eigendecompositions of error covariances, using ESSE. The optimal strategies were subject to weather and operational constraints. Figure 6 shows the multiplicity of scales of such strategies. The R/V Able-J (Panel a) was used to sample the

Fig.6 – Adaptive sampling methodologies carried out in real-time for two months. (a) The R/V Able-J was used to sample the Bay scales and the external oceanic forcings. (b) The R/V Oceanus sampled the mesoscales, outside of Cape Cod Bay, and in the open boundary forcing regions. (c) The R/V Lucky Lady sampled the mesoscale and submesoscales (d), mainly in Cape Cod Bay. (e) The Odyssey AUV's sampled the submesoscales in Cape Cod Bay. (f) The REMUS AUV's sampled the turbulent scales in Cape Cod Bay.



Bay scales and the external oceanic forcings (note the adapted zigzag in the Gulf of Maine and over Georges Bank). The R/V Oceanus (Panel b) sampled the mesoscales, outside of Cape Cod Bay, and in the open boundary forcing regions. The R/V Lucky Lady sampled the mesoscale (Panel c) and submesoscales (Panel d), mainly in Cape Cod Bay. The Odyssey AUV's (Panel e) sampled the submesoscales in Cape Cod Bay. Finally, the REMUS AUV's (Panel f) sampled the turbulent scales in Cape Cod Bay. All of the sampling patterns of these platforms and sensors were designed and made available in real-time, assimilating yesterday's data today for tomorrow's forecast and sampling. These accomplishments have resulted in a combined and compatible physical and biological multi-scale data set applicable to interactive process studies and data assimilation, adaptive sampling, and predictive skill OSSEs.

Coastal Predictive Skill Experiments at LEO-15: A series of Coastal Predictive Skill Experiments (CPSE) were begun at LEO-15 starting in 1998. The summer 1998 CPSE focused on improving nowcast skill for adaptive sampling using spatially extensive real-time data. The summer 1999 CPSE focused on improving model forecast skill for adaptive sampling via coupling to a regional atmospheric model, improved turbulent closure, and real-time updates of the offshore boundary conditions. Future CPSEs will emphasize the coupling between physical and bio-optical components.

The phenomenological focus of the CPSEs is the development of recurrent coastal upwelling centers and their effect on phytoplankton and suspended sediment distributions. Figure 7a illustrates the initial development of an upwelling center in which the ocean model has assimilated the more

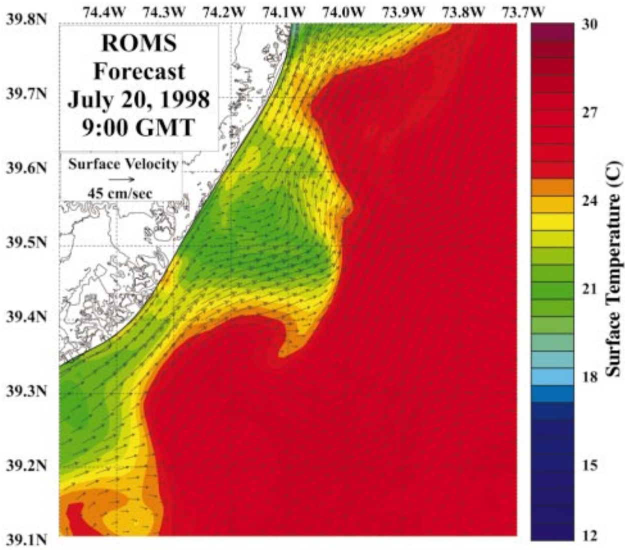


Fig. 7(a) – Sea surface temperature and surface current forecast of the initial formation of an upwelling center generated by the Regional Ocean Modeling System (ROMS) forced with operational Navy atmospheric forecasts while assimilating surface current radial velocity components from the individual CODAR sites.

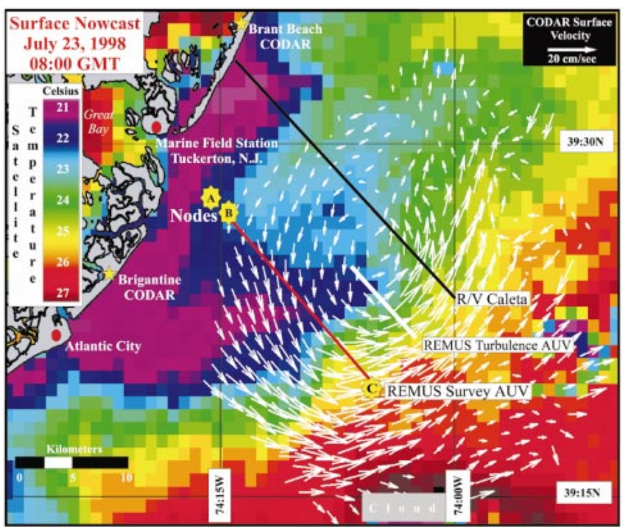


Fig. 7(b) – Sea surface temperature and surface current nowcast of a fully-developed upwelling center derived by detiding and low-pass filtering the combined CODAR vector velocities. Lines indicate the locations of the three cross-shelf repeat transects chosen for subsurface shipboard and AUV sampling.

extensive radial currents from each of two on-shore CODAR HF-Radars (Kohut *et al.*, 1999). The initial development is characterized by the cyclonic curvature in the northward flowing upwelling jet and the surfacing of the cold upwelled water nearshore.

Three days later, the surface current and temperature nowcast indicated that the upwelling jet was now meandering around a cyclonic eddy embedded within the cold upwelling center (Figure 7b). This data-based nowcast, a model forecast for continued upwelling, and model sensitivity studies indicating a dependence on turbulent closure in the vicinity of the eddy, were used to define three cross-shelf transects for sampling over a two day period. A ship-towed SWATH ADCP and an undulating CTD/Fluorometer (Creed *et al.*, 1998) were sent to patrol the transect just north of the eddy center, and a REMUS survey vehicle was sent to patrol the transect just south. The REMUS turbulence vehicle was sent directly into the eddy center to observe the changing turbulence characteristics as the vehicle drove out of the eddy and crossed the upwelling front.

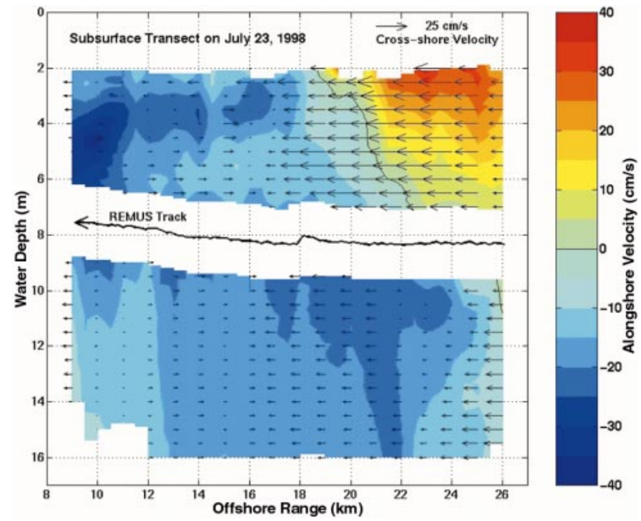


Fig. 8 – Alongshore (color contours) and cross-shore (arrows) velocity components derived from the upward and downward looking ADCPs on the REMUS Survey AUV as it ran shoreward along the southern transect at a depth near 8 m.

The alongshore current component (Figure 8, color contours) acquired by the REMUS survey vehicles not only indicates that the northward-flowing upwelling jet on the offshore side is confined to the region above the thermocline, it also reveals a southward-flowing, subsurface jet on the nearshore side. The systems towed along the northern transect uncovered a similar velocity structure, with the highest phytoplankton concentrations of the season discovered within the subsurface jet. The subsurface adaptive sampling data suggest that phytoplankton concentration increases within the upwelling center may be dominated by advection from the north.

Eddy viscosities derived from the REMUS turbulence vehicle were found to be two orders of magnitude greater on the inshore side of the upwelling front compared to the offshore side. Idealized tests of the modified KPP closure (Figure 9) indicate that maximum eddy viscosities are expected just shoreward of the upwelling front. Standard

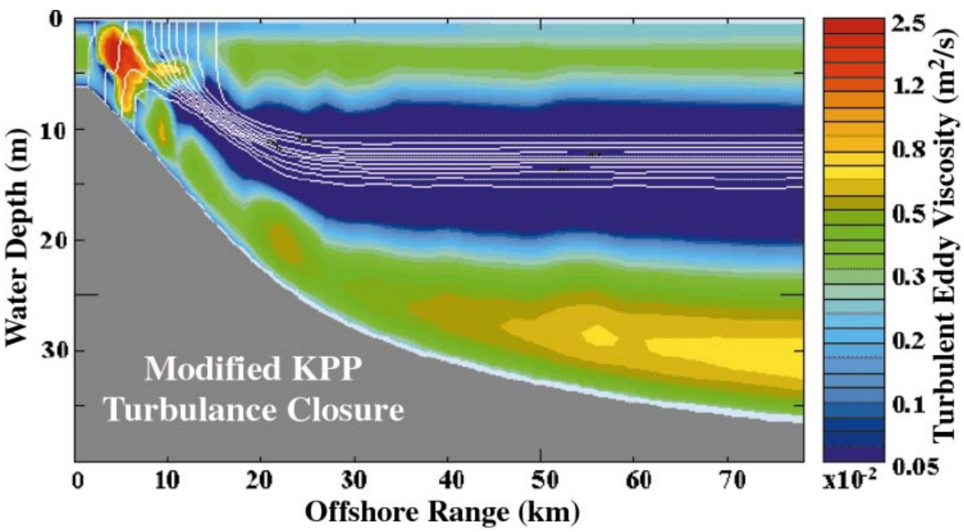


Fig. 9 – Idealized cross-shelf transect of turbulent eddy viscosity (color contours) and density (white lines) generated by the modified KPP closure, with the largest viscosities found shoreward of the density front.

turbulent closure schemes produce the exact opposite, a minimum in the eddy viscosity just shoreward of the front. Coupled biological model sensitivity studies indicate that the biological response can be even more sensitive to vertical mixing parameterizations than the physical model.

Adaptive sampling research and the control of errors

In modern ocean adaptive sampling, a goal characterizes the ideal future sampling among the possible choices, in an adaptive accord with the constraints and available forecasts that have assimilated all of the past data. This goal can be achieved either subjectively, with forecast information being combined with the *a priori* experience to intuitively choose the future sampling, or quantitatively, where forecast capabilities serve as input to a mathematical sampling criterion whose real-time, continued, optimization predicts the adapted sampling. The parameters of the adaptive sampling procedure are therefore the available forecasts, new data acquired during the forecast, the constraints and the goal, i.e. the properties to be optimized and the metrics used to measure these properties.

Today, the forecast capabilities include the future evolution of the ocean fields, of their variabilities and of their uncertainty or error statistics (Lermusiaux, 1999). There are constraints from practical considerations (platforms and sensors available, airport locations, ship speeds, AUV range, weather conditions, etc), dynamical motives (search for precursor of the primary phenomenon, dynamical model verifications), and cost penalties (batteries, fuel, human costs). There are scientific and technical constraints for the measurement model to generate the actual state variables to be assimilated. For example, adaptive sampling of coastal currents may be severely constrained by the sampling requirements of a measurement model that separates the frequencies of interest (the model velocity state variables for assimilation) from the spectrum of frequencies observed (surface and internal waves, tides, inertial waves, etc.). Finally, several goals or criterion are also possible, in varied representations (e.g. physical vs. Fourier space). For example, the optimum can be the sampling that minimizes the forecast of the field error variances over the global domain and scales of interest, subject to the cost penalties and practical constraints. Other types of optima are the sampling that ideally determines specific properties of the future dynamics (e.g., potential vorticity), irrespective of the past data and other constraints, or, the sampling that allows the best skill evaluation. In assimilation studies, the goal should be in accord with the data assimilation criteria. For example, if the assimilation aims at minimizing the field error with a variance metric (i.e. trace of the error covariance), the adaptive sampling criteria should aim at determining the future sampling that also minimizes the trace of the error covariance.

An important component involves the theoretical and numerical optimization procedure, to be carried out in real-time. For linear systems, the optimization can be implemented beforehand, independently of the future data values, only using the dynamical and measurement models and their statistical uncertainties. However, for nonlinear models, the data values matter, and forecast OSSEs need to be carried out during the optimization process. To do so, the results of the last decades in optimal control and estimation theory (Robinson *et al*., 1998) are ready to be utilized and further developed by the interdisciplinary oceanographer in the quest for the most useful data.

Research Directions and Future Prospects

During the 1990’s interdisciplinary ocean science has been rapidly evolving and now comprises an increasingly important and substantial component of marine science. This has been based upon progress in the understanding of realistic ocean dynamical processes in the sub-disciplines, and the identification of new realistic coupled and interdisciplinary dynamical processes is presently a research frontier. More and more attention is being focused on the coastal ocean and its deep sea and terrestrial interactions. The requisite four dimensional field estimates necessary for continued progress in multi-scale interdisciplinary ocean science and technology can only be provided by advanced littoral ocean observing and prediction systems with adaptive sampling. Ocean science, ocean engineering and marine technology are symbiotic among themselves and are deeply rooted in the fundamental and engineering sciences. Complex ocean systems research today is interdisciplinary with important aspects of computer, information and communication sciences.

Coastal ocean adaptive sampling is in its infancy and methodological advances in the next several years will be related to advances in the observing and prediction systems components, the overall system concept and system integration, as well as dedicated theoretical research on objective, automated sampling. Platform advances will include ocean gliders, improved AUV capabilities and unmanned aircraft. Fleets of robotic autonomous platforms will operate with sampling patterns altered in consideration of data pooled and analyzed aboard command platforms. New sensors are under design, construction and test for hyperspectral ocean optics, microwave salinity and coastal altimetry measurements. Interdisciplinary multi-scale ocean models will be validated for a variety of (interactive) processes; calibration and sensitivity procedures will be established. Process feedbacks for coupled regional atmospheric and oceanic models will be better understood and some coupled systems will be undergoing verification from both regional and generic points of view. Research issues involved in developing the methodology of quasi-optimal assimilation of interdisciplinary multi-scale multi-fields in real-time should be clarified. The advanced OOPS concept is of a flexible, modular, scaleable, distributed system capable of efficiently managing large pre-existing and novel databases. Fully integrated OSSEs, which include both scientific process and engineering operational constraints, will be underway. The suitability of adaptive sampling goals for various purposes will be studied and better understood and, hopefully, associated quantitative metrics will not be strongly dependent upon the methodology of their implementation. With recent progress towards the implementation of real-time optimal control and optimization algorithms, computed optimal samplings will give the assimilation scheme the observations it needs most, hence ideally improve the ocean field estimate. Such theoretical adaptive sampling studies need to be carried out for both covert and overt operations.

Experience of recent past decades indicates that the first decade of the twenty first century should result in the maturing and evolution of both interdisciplinary ocean science and technology, and the ocean observing and prediction system concept. Powerful new field estimation and regional predictive capabilities can be expected to transform overall operational capabilities for naval rapid environmental assessment and societal environmental crisis response and, supported by rapidly expanding observational infrastructure and a strong national coastal program, to provide the basis for effective and efficient management of multi-use coastal zones.

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References

1. K.H. Brink, “Observational coastal oceanography,” presented at Advances and Primary Research Opportunities in Physical Oceanography Studies (APROPOS) Workshop, 15-17 December 1997.

2. E.L. Creed, S.M. Glenn and R. Chant, Adaptive Sampling Experiment at LEO-15, OCC ’98 Proceedings, *Sea Technology*, November, 576-579 (1998).

3. T.B. Curtin, J.G. Bellingham, J. Catipovic and D. Webb, “Autonomous Ocean Sampling Networks,” *Oceanography*, **6**(3), 86-94 (1993).

4. S.M. Glenn, G.Z. Forristall, P. Cornillon and G. Milkowski, “Observations of Gulf Stream Ring 83-E and Their Interpretation Using Feature Models,” *J. of Geophysical Research*, **95**, 13,043-13,063 (1990).

5. S.M. Glenn and A.R. Robinson, “Verification of an Operational Gulf Stream Forecasting Model,” *Qualitative Skill Assessment for Coastal Ocean Models, Coastal and Estuarine Studies*, American Geophysical Union, D. Lynch and A. Davies (eds.), **47**, 469-499 (1995).

6. S.M. Glenn, D.B. Haidvogel, O.M.E. Schofield, J.F. Grassle, C.J. von Alt, E.R. Levine and D.C. Webb, “Coastal Predictive Skill Experiments at the LEO-15 National Littoral Laboratory,” *Sea Technology*, April, 63-69 (1998).

7. J.F. Grassle, S.M. Glenn and C. von Alt, “Ocean Observing Systems for Marine Habitats,” OCC ’98 Proceedings, *Sea Technology*, November, 567-570 (1998).

8. T.R. Keen and S.M. Glenn, “Factors influencing hindcast skill for modeling shallow water currents during Hurricane Andrew,” *J. Atmos. Ocean. Tech*., **15**, 221-236 (1998).

9. J.T. Kohut, S.M. Glenn and D.E. Barrick, “SeaSonde is Integral to Coastal Flow Model Development,” *Hydro International*, April, 32-35 (1999).

10. W.G. Large, J.C. McWilliams and S.C. Doney, “Oceanic vertical mixing: A review and model with a nonlocal boundary layer parameterization,” *Reviews of Geophysics*, **32**, 363-403 (1994).

11. P.F.J. Lermusiaux, “Data assimilation via error subspace statistical estimation, Part II: Mid-Atlantic Bight shelfbreak front simulations and ESSE validation,” *Monthly Weather Review*, **127**(8), 1408-1432 (1999).

12. MODE Group, “The Mid-Ocean Dynamics Experiment,” *Deep-Sea Research*, **25**, 859-910 (1978).

13. C.N.K. Mooers, A.R. Robinson and J.D. Thompson, “Ocean Prediction Workshop 1986: A status and prospectus report on the scientific basis and the Navy’s needs,” *Proceedings of Ocean Prediction Workshop*, Inst. Naval Oceanography, National Space Technology Laboratory, MS.

14. S. Nadis, “’Real-time’ oceanography adapts to sea changes,” *Science*, **275**, 1881-1882 (1997).

15. N.M. Patrikalakis, P.J. Fortier, Y.E. Ioannidis, C.N. Nikolaou, A.R. Robinson, J.R. Rossignac and A. Vinacua, “Distribution Information and Computation in Scientific and Engineering Environments.” *D-Lib Magazine*, **5**(4), http://www.dlib.org/dlib/april99/04abrams.html (1999).

16. E. Pouliquen, A.D. Kirwan Jr. and R.T. Pearson (eds.), “Rapid Environmental Assessment,” *Proceedings Int. Conference Rapid Environmental Assessment*, 10-14 March 1997, Lerici, Italy.

17. A.R. Robinson (ed.), *Eddies in Marine Science* (Springer, Berlin, 1983), p. 609.

18. A.R. Robinson, “Forecasting and simulating coastal ocean processes and variabilities with the Harvard Ocean Prediction System” *Coastal Ocean Prediction*, AGU Coastal and Estuarine Studies Series, C.N.K. Mooers (ed.), (American Geophysical Union, 1999), pp. 77-100.

19. A.R. Robinson and K.H. Brink (eds.), *THE SEA: The Global Coastal Ocean, Volume 11: Regional Studies and Syntheses*, (John Wiley and Sons, New York, 1999).

20. A.R. Robinson, J.A. Carton, N. Pinardi and C.N.K. Mooers, “Dynamical forecasting and dynamical interpolation: An experiment in the California Current,” *J. of Physical Oceanography*, **16**, 1561-1579 (1986).

21. A.R. Robinson, P.F.J. Lermusiaux and N.Q. Sloan, “Data Assimilation,” *THE SEA: The Global Coastal Ocean, Volume 10: Processes and Methods*, A.R. Robinson and K.H. Brink (eds.), (John Wiley and Sons, New York, 1998), pp. 541-594.

22. B.A. Rothschild, A. Robinson, A. Gangopadhyay, S. Besiktepe, J. Bisagni, A. Cabeza, D. Cai, P. Fortier, P. Haley, H.S. Kim, E. King, L. Lannerole, P. Lermusiaux, W. Leslie, C. Lozano and M. Miller, “Management Information System and the Precautionary Approach,” ICES Symposium on Confronting Uncertainty in the Evaluation and Implementation of Fisheries-Management Systems, 16-19 November 1998, Cape Town, South Africa.

23. J. Sellschopp and A.R. Robinson, “Describing and forecasting ocean conditions during Operation Rapid Response,” *Proceedings Int. Conf. Rapid Environmental Assessment*, E. Pouliquen, A.D. Kirwan Jr. and R.T. Pearson (eds.), 10-14 March 1997, Lerici, Italy, pp. 35-42.

24. R. Styles and S.M. Glenn, “Modeling Stratified Wave-Current Bottom Boundary Layer Model for the Continental Shelf,” *J. of Geophysical Research*, submitted (1999).

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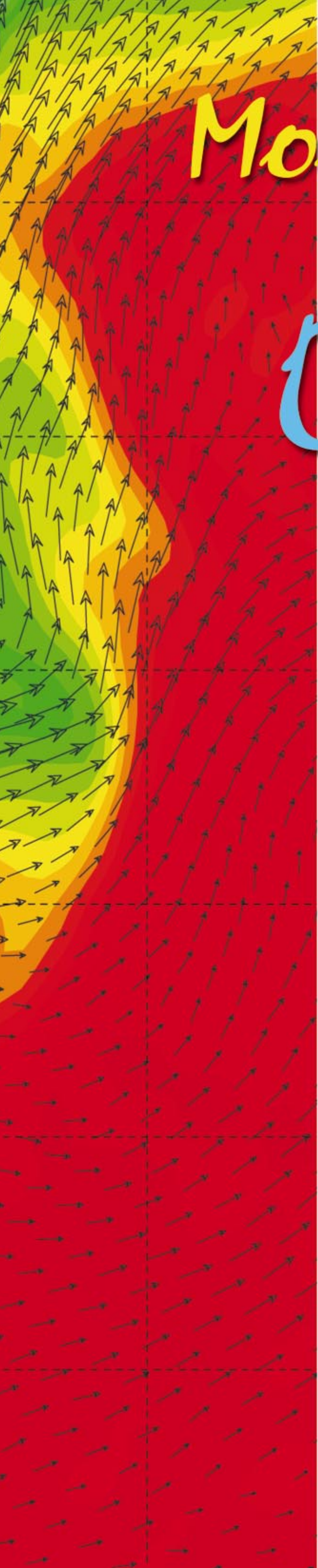

Modeling by Assimilation

Oceanographers have recently made considerable strides in model improvement, model-data synthesis, and oceanic and climatic forecasting. They are moving towards forecasting applications that vary from global climate change simulations, through modeling of decadal and interannual climate variabilities like *El Niño*, to extended seasonal forecasts, and finally to regional forecasts on a time scale of weeks.

Advances in data assimilation have been largely responsible for the new ability to take good advantage of the rapidly expanding dataset. These advances come not only from meteorology, but from work as divergent as solid-earth geophysics inverse theory and engineering control theories. All of them have helped oceanographers by giving them the formal tools necessary to constrain a dynamical model with available data.

Different oceanographic applications call for different data assimilation methodologies. The diversity of the objectives suggests that no single assimilation methodology can address all of our needs. More probably several techniques, like those addressed in the article that follows, will jointly address the future needs of oceanographic assimilation. Each methodology will serve the purposes to which it is best suited.

Here then is a review of some of this decade's most promising work.

- J.P.

Oceanographic Data Assimilation in the 1990s: Overview, Motivation and Purposes

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Abstract

A brief non-technical overview is given of oceanographic data assimilation in the 1990's. First, a historical perspective is presented that illustrates its main motivations and discusses the objectives of combining fully complex ocean general circulation models (OGCM) and oceanographic data. These objectives are divided into three main categories: model improvement, model-data synthesis and ocean/climate forecasting. Forecasting applications vary from global climate change simulations on a time scale of 50-100 years; through decadal and interannual climate variability, such as the El Nino-Southern Oscillation and the Atlantic thermohaline variability; to extended seasonal forecasts and finally to regional forecasts on a time scale of a few weeks. Appropriate assimilation methodologies for each class of oceanographic applications are discussed. For each ocean prediction problem on different time/space scales the needs for data assimilation approaches are pointed out where these are still lacking as they might overcome some of the present deficiencies of the related modeling efforts.

Introduction

The term "data assimilation" emerged in meteorology about 30 years ago to describe a methodology in which observations are used to improve the forecasting value of operational meteorological models. In the practice of operational meteorology, all the observations available at prescribed times are "assimilated" into the model by melding them with the model-predicted values of the same variables in order to prepare initial conditions for the forecast model run.

In the oceanographic context, however, "data assimilation" has acquired a much broader meaning, covering a vast body of methodologies that originate not only in meteorology, but also in solid-earth geophysics inverse theories and in engineering control theories. These methods all constrain a dynamical model with available data. Furthermore, oceanographers often use data assimilation for very different purposes than those common in meteorology. In this past decade they have come to focus on "model-data synthesis", that is, on obtaining a four-dimensional realization (the spatial description coupled with the time evolution) of the oceanic flow that is simultaneously consistent with the observational evidence and the dynamical equations of motion. This "synthetic" realization can be used for detailed process studies.

In this paper I wish to provide a brief and non-technical overview of the various assimilation problems and methodologies used in oceanography. My main focus is the objectives of oceanographic data assimilation, rather than the methodologies used, and I will try to concentrate on what still needs to be done rather than on reviewing the existing body of work. I limit my attention to the use of oceanographic data with the most realistic and sophisticated tools presently available to simulate oceanic flows, the ocean general circulation models (OGCM). One assumes the future of oceanographic data assimilation must lie there.

Many detailed technical references cover the various assimilation methodologies used in oceanography. At the most fundamental levels, inverse methods in oceanography are similar to those used in geophysics. Some comprehensive textbooks for this mature field are *Geophysical Data Analysis: Discrete Inverse Theory* by Menke (1984) and *Inverse Problem Theory* by Tarantola (1987). However, these reviews do not meet oceanography's requirement: an analysis of these methods for application to nonlinear, time-dependent dynamical models of three-dimensional ocean circulation. Data assimilation methods most used and relevant for meteorology are reviewed by Bengtsson *et al.* (1981). From the point of view of the complexity of the physical systems, and of the associated dynamical models, the analysis and applications discussed in Daley's (1991) book, *Atmospheric Data Assimilation*, are perhaps the most useful.

Two major differences in objective still prevent oceanography from simply "borrowing" techniques from meteorology. First, the motivation for oceanic data assimilation, is not as narrowly focused on short term prediction as most meteorological efforts, although it must be added that ocean forecasting is rapidly emerging as a legitimate and important motivation in itself. Second, the meteorological and oceanographic data sets are distinguished from one another by a major difference, which I will discuss in the next section. Thus methodologies that originate in meteorology cannot be blindly applied to oceanic dynamical problems, but must be revisited and sometimes profoundly modified to make them feasible and successful for physical oceanography.

Reviews and syntheses of data assimilation methods for oceanographic applications can be found in the special issue of *Dynamics of Atmospheres and Oceans* devoted to Oceanographic Data Assimilation, Haidvogel and Robinson, eds. (1989). The review paper by Ghil and Malanotte-Rizzoli (1991) provides a very comprehensive review of the literature up to the early 90's. A recent, thorough synthesis of oceanographic assimilation methodologies appears in Bennett (1992). A recent monograph by Wunsch (1996) views ocean general circulation as an inverse problem.

Historical perspective

Over the past 25 years or so, since the initial efforts to develop three dimensional ocean circulation models (Bryan, 1969), ocean modeling has made enormous progress. Holland and Capotondi (1996) review the milestones in the development and advancement of OGCM's, up to the complexity and sophistication of the present generation of models, which are capable of most realistic simulations on the global scale. Their review also offers a perspective from which to view the future possibilities and trends of ocean modeling. In parallel with advances in modeling, oceanic observational techniques have also been thoroughly revolutionized. However, because oceanography lacks a single focusing motivation for oceanic data assimilation like the one meteorology gets from the need for Numerical Weather Prediction (NWP), ocean models and observational techniques have developed quite independently of one another. When oceanic models and observations started to converge, they did so along different paths depending on the specific objective of each effort.

The early days of oceanography saw dynamic calculations as the main quantitative tool to combine data (temperature and salinity) with "models" (thermal wind relations). From this modest beginning—relying on highly simplified models with no formal assimilation procedure—the next step was to introduce a formal least square inverse methodology imported from solid earth geophysics and add the tracer conservation constraints in order to solve the problem of the level of no motion (Wunsch, 1978; Wunsch and Grant, 1982; Wunsch, 1989a,b). This was done in the framework of coarse resolution box models whose dynamics was still very simple, although the inverse methodology used was very general.

At the other extreme of model complexity versus assimilation method sophistication, efforts began with "diagnostic models" in which temperature and salinity data were simply inserted into the dynamical equations of fairly complex ocean models in order to evaluate the velocity field (Holland and Hirschman, 1972). The results were very poor because of inconsistencies in model-data-topography, and so at the next stage a very simple assimilation methodology was introduced into OGCMs, and this became known in the oceanographic context as the "robust diagnostic" approach (Sarmiento and Bryan, 1982). The same approach had actually been introduced earlier in meteorology as the "nudging" technique (Anthes, 1974) and the term "nudging" has now become common in oceanography as well. In this approach there is no effort to introduce least-square optimality, and the data are just used to nudge the model solution towards the observations at each time step through a relaxation term added to the model equations. The result is far superior to simple diagnostic models, but leaves much to be desired due to the inability to use information about data uncertainty or to estimate the errors in the solution obtained (Holland and Malanotte-Rizzoli, 1989; Capotondi *et al.*, 1995a,b; Malanotte-Rizzoli and Young, 1995).

As the objectives of modeling and observational oceanography began to converge, more formal least square methods taken from meteorology were also used in ocean models, in particular the Optimal Interpolation (OI) method (Robinson *et al.*, 1989; Derber and Rosati, 1989; Mellor and Ezer, 1991 are among the first examples). OI may be viewed as a nudging technique in which the amount of nudging of the model solution towards the observations depends on the data errors, while also permitting error estimates for the solution. This approach, developed in meteorology for NWP, cannot improve model parameters or parameterizations, nor can it fit the entire four-dimensional distribution of observations simultaneously to the model solution. However, due to OI's relatively low computational cost, it remains appropriate for higher resolution, short-term prediction and state estimation purposes.

Carrying the least square approach for a time dependent model to its rigorous limit leads to the "Kalman filter/smoother" assimilation methodology, which can assimilate data into a time dependent model while assuring least-square optimality, full use of *a priori* error estimates, and calculation of the covariance error matrix for the model outputs. Apart from the fact that the Kalman filter is formally optimal in the least-square sense only for linear models, its high computational cost limits its use at present to simple models or very coarse OGCMs. Recent efforts are directed at developing efficient although suboptimal variants of the Kalman filter/smoother that allow the use of a full nonlinear OGCM with this method (Fukumori *et al.*, 1993; Fukumori and Malanotte-Rizzoli, 1995; Menemenlis *et al.*, 1997a,b; Cane *et al.*, 1998; Verron *et al.*, 1999).

The ultimate goal of combining a formal least-square optimization approach with a full complexity OGCM requires simultaneous solution of hundreds of thousands of coupled nonlinear equations (the model equations at all grid points and all time steps), and therefore requires an efficient approach. Such an approach can be found in the "optimal control" engineering literature. Also known as the "adjoint method", this method is capable of model improvement, parameter estimation and true four-dimensional data assimilation. It is equivalent in principle to the Kalman filter (Ghil and Malanotte-Rizzoli, 1991), except that it allows us to give up the use and calculation of full covariance matrices, and therefore is more computationally feasible for higher resolution nonlinear OGCMs (Tziperman and Thacker, 1989; Tziperman *et al.*, 1992a,b; Marotzke, 1992; Marotzke and Wunsch, 1993; Bergamasco and P. Malanotte-Rizzoli, 1993; Yu and Malanotte-Rizzoli, 1996; Lee and Marotzke, 1997, 1998; Yu and Malanotte-Rizzoli, 1998). The most recent application of the methodology involves the evaluation of an adjoint code for complex OGCM's through an automatic compiler (Marotzke *et al.*, 1999).

The development of assimilation methods in physical oceanography seemed always to trail a few years behind meteorology. Given that the ocean and atmosphere, even though characterized by some important differences, are similar enough that they can be treated with the same theoretical approaches and methodologies, such a lag can be surprising. It is therefore important for the ocean modeler to try to understand why meteorology and oceanography have seen different rates of development of data assimilation methodologies in order to isolate potential obstacles to their future use in oceanography.

Clearly a primary reason for the delayed development of oceanic data assimilation was the lack of an urgent and obvious motivation such as generating better and longer weather forecasts provided meteorology. This situation has been rapidly changing in recent years, and ample motivation for ocean data assimilation now exists because of the need for systematic model improvement and ocean state estimation. The need for ocean prediction is now emerging on various temporal and spatial scales: from climate change predictions, through regional forecasts of the large scale ocean climate variability (of for example the North Atlantic thermohaline circulation or *El Niño* in the Pacific Ocean), to thefew weeks' regional mesoscale ocean forecasts in frontal regions like the Gulf Stream system that for example various Naval applications require.

Want of an obvious motivation aside, however, the most profound limitation on the development of oceanic data assimilation may have been the lack of adequate data sets. The number of available oceanographic observations is far smaller than the number of meteorological observations, especially when the different temporal and spatial scales are considered. It is estimated, in fact, that the number of presently available oceanographic observations is smaller than its meteorological counterpart by several orders of magnitude (Ghil and Malanotte-Rizzoli, 1991; Daley, 1991).

New oceanographic data sets, nearly comparable to the meteorological one, that is, synopses with with global coverage, are however becoming available. This oceanographic observational revolution of the 90's has been made possible by the advent of satellite oceanography. Already ~40,000 sea surface temperatures are now available daily on a global scale, measured by the NOAA satellites that have been flying since the 80's. Additionally, two satellite altimeters are now providing observations of the ocean surface topography that is tightly coupled to ocean currents. The first of these, TOPEX/POSEIDON, was launched in 1992, and is currently producing global maps of sea surface height with a horizontal resolution of ~300 km x 300 km at mid-latitudes every 10 days, and at an impressive accuracy of 5cm (Stammer and Wunsch, 1994). TOPEX/POSEIDON altimeter data provide powerful information to inverse approaches for determination of the large-scale ocean circulation (Stammer and Wunsch, 1996; Ganachaud *et al.*, 1997). The European satellite ERS-1 is also measuring sea surface topography with higher spatial resolution that resolves the mesoscale eddy field. ERS-1 also measures the surface wind field on the global scale at a 1 degree resolution, providing thereby information about a crucial driving force of oceanic circulation. Fu and Fukumori (1996) review the effects of errors in satellite altimetry for constraining OGCM's through data assimilation.

A second major source of worldwide oceanographic observations is the World Ocean Circulation Experiment (WOCE). Through basin-wide hydrographic sections, both meridional and zonal, the WOCE should provide a zero-order picture of the large scale global circulation in the 90's. Because hydrographic sections are not synoptic, and are mostly carried out only once, no data of the time evolution will be available and very large water bodies between adjacent sections still remain void of data. Hence the great importance of numerical models endowed with data assimilation capability to act as dynamical interpolators and extrapolators of the oceanic motions. Clearly ocean models and assimilation methods can make better use of the various new and traditional sources of oceanographic data when reliable error estimates are available. Particularly important is the possibility of obtaining estimates of the non-diagonal terms of the error covariance matrices, for which only the diagonal terms, i.e. the data standard deviations, are usually specified. Hogg (1996) discusses efforts to obtain estimates of the full error covariances of traditional oceanographic datasets (Figure 1 and 2).

It is worthwhile to mention another type of oceanic observation, rather different from traditional point-wise measurements. These are the observations provided by ocean acoustic tomography that exploits the ocean's transparency to sound. As in its more familiar medical application, the tomographic technique scans the ocean through two-dimensional (vertical or horizontal) slices using sound waves. The difference and novelty of ocean acoustic tomography lies in the integral nature of the tomographic datum (Munk *et al.*, 1995). The implications and need for the assimilation of such integral data into OGCM's are discussed by Cornuelle and Worcester (1996). A first estimate of the North Pacific general circulation by combining satellite altimetry, acoustic tomography and an OGCM was provided by the ATOC Consortiuim (1998).

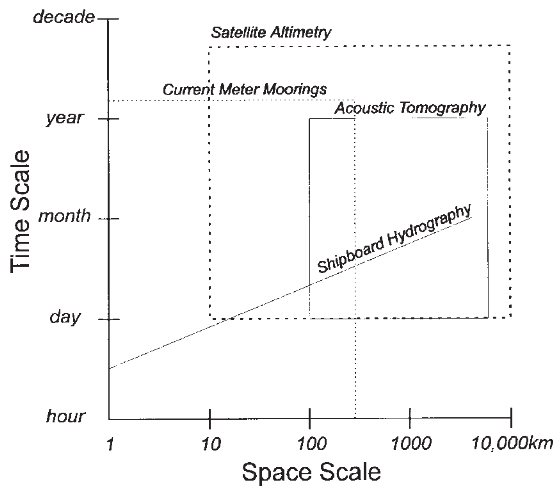

Fig. 1 – Space and time scales accessible by various measurement techniques. [From Hogg, 1996]

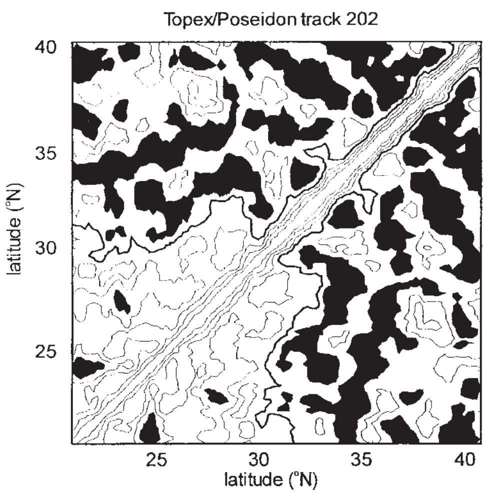

Fig. 2 – A correlation matrix of sea surface height measured along Topex/ Poseidon descending track no. 202 which crosses 20°N at about 55°W and 40° N at about 68° W. filled areas are between -0.2 and zero. [From Hogg, 1996]

This brief discussion of the emerging need for ocean data assimilation and the new data sets that are becoming available indicates that the limitations imposed by the scarcity and non-synopticity of oceanic observations are being overcome. Oceanographic data assimilation can now become a fully developed, mature field.

Objectives of oceanographic data assimilation

Efforts to combine fully complex OGCMs and oceanographic data may roughly be divided into three main categories: model improvement, model-data synthesis with related studies of dynamical processes through state estimation, and, finally, oceanic/climatic forecasting. Let us consider these objectives in some detail, as well as the assimilation methodologies relevant to each.

Even the highest resolution ocean circulation models cannot resolve all of the dynamically important physical processes in the ocean from small scale turbulence to basin scale currents. There will always be processes that are not represented directly, but are instead parameterized. These parameterizations are sometimes simple, often complicated, and always quite uncertain both in form and in the value of their tunable parameters. Very often the uncertainty in these parameterizations is accompanied by an extreme sensitivity of the model results to slight variations in the parameters. An obvious though not unique example is the parameterization of small scale vertical mixing in the ocean interior for which many forms have been proposed. This drastically affects the strength of the thermohaline circulation and the estimate of meridional heat flux of OGCMs (Bryan, 1987). Other examples are the parameterizations of mixed layer dynamics (Mellor and Yamada, 1982), and of deep water formation (Visbeck *et al.*, 1996).

The most important example of the need to parameterize the sub-grid scale motions not resolved by the OGCM resolution is provided by the parameterization of mesoscale eddies in coarse OGCM's used for climate studies. The traditional horizontal eddy diffusivities have been proven grossly inadequate, inducing spurious features into the simulations like the strong artificial upwelling different OGCM's produce in the mid-latitude North Atlantic inshore of the Gulf Stream (Böning *et al.*, 1995). Testing of different proposed parameterizations, such as those by Green (1970), Stone (1972), and Gent and McWilliams (1990), has been extensively discussed in the recent literature, including notably the work by Böning *et al.* (1995). For a most recent review of the assessment of different eddy parameterizations see Jiang *et al.* (1999).

Another set of uncertain yet crucial parameters corresponds to the poorly known surface forcings by wind stress, heat fluxes and evaporation and precipitation, all of which are subject to typical uncertainties of 30-50% (Trenberth *et al.*, 1989; Schmitt *et al.*, 1989; Trenberth and Solomon, 1994).

Finally, a crucial problem that needs to be solved if regional models are to improve is the specification of open boundary conditions. The open-boundary condition problem is mathematically ill-posed and *ad hoc* boundary conditions, mostly empirically determined, are prescribed (Chapman, 1985; Robinson *et al.*, 1989; Malanotte-Rizzoli and Young, 1995). Data assimilation approaches can provide a powerful tool for improving regional ocean models.

The first major objective of oceanographic data assimilation is to use the available data systematically and quantitatively in order to test and improve the various uncertainties of OGCMs. It is important to understand that by model improvement I mean the use of data to determine model parameters, forcing functions, boundary conditions, etc. in a way that will yield better performance when the model is later run *without* data assimilation. There are typically thousands of poorly known internal model parameters, such as viscosity/diffusivity coefficients at each model grid-point, and many thousands more if the surface forcing functions are included at every surface grid point (Tziperman and Thacker, 1989). Estimation of these parameters therefore becomes an extremely complicated nonlinear optimization problem whosesolution requires efficient methodologies and powerful computers. The assimilation methodology most suited to deal with these estimation problems is the adjoint method that calculates the model sensitivity to its many parameters (Hall and Cacuci, 1983; Thacker, 1988; Thacker and Long, 1988)

To my knowledge only one application of the adjoint procedure has been carried out so far for the optimal estimation of eddy viscosity parameters. This was done by Tziperman and Thacker (1989) using simplified model dynamics and an idealized basin configuration. On the other side, the adjoint approach has proven very successful in the estimation of surface forcings (wind stress, surface heat and moisture fluxes) with OGCMs in fully realistic configurations. See the study by Marotzke and Wunsch (1993) and the more recent ones by Yu and Malanotte-Rizzoli (1996), Lee and Marotzke (1997), Yu and Malanotte-Rizzoli (1998), and Lee and Marotzke (1998). Equally successful has been the inclusion of open boundary conditions as control variables in the adjoint code, as shown by Gunson and Malanotte-Rizzoli (1996a,b) for simplified dynamics and idealized model configurations, and by Zhang and Marotzke (1999) for a fully realistic application of an OGCM to the Indian ocean.

Even though extensive data sets are becoming available through the new remote sensing methods and the extensive global observational programs mentioned above, the ocean remains only sparsely observed. Most of the interior water mass, and especially the abyssal layers, will continue to remain unmonitored. Hence the second major objective of oceanic data assimilation is to have numerical models constrained to reproduce the available observations act as dynamical extrapolators and interpolators, propagating information to times and regions void of data. This approach is now defined as “model-data synthesis” and has received tremendous impetus in recent years.

Synthesizing the ocean state from observations may serve several important goals. On a global scale, unobservable quantities such as the meridional heat flux and the air-sea exchanges can be continuously monitored from the assimilation output to infer possible changes due to climate trends. Knowledge of the natural variability of these quantities is essential for us to differentiate natural climate variability from man-induced climate change. On a regional scale, we see how high resolution, eddy resolving interpolation of remote sensing or localized data by the models (Mellor and Ezer, 1991; Capotondi *et al.*, 1995a,b; Malanotte-Rizzoli and Young, 1995) provides a four dimensional picture of the eddy field. This picture can then be used to study detailed dynamical processes of eddy-mean flow interaction, ring formation and ring/jet interactions in the energetic western boundary currents.

Global model-data synthesis may be seen in the estimates of the global circulation by Sirkes and Tziperman (1996) and those which Stammer *et al.* (1997) obtained through the adjoint method. Basin-scale examples, again based on the adjoint procedure, are found in Marotzke and Wunsch (1993), Yu and Malanotte-Rizzoli (1996, 1998), and Lee and Marotzke (1997, 1998). The applications by Menemenlis *et al.* (1997a,b) use a suboptimal Kalman filter. In the tropical ocean, Busalacchi (1996) shows how the unique physics of the low-latitude oceans and the wealth of observational data from the Tropical Ocean Global Atmosphere program have

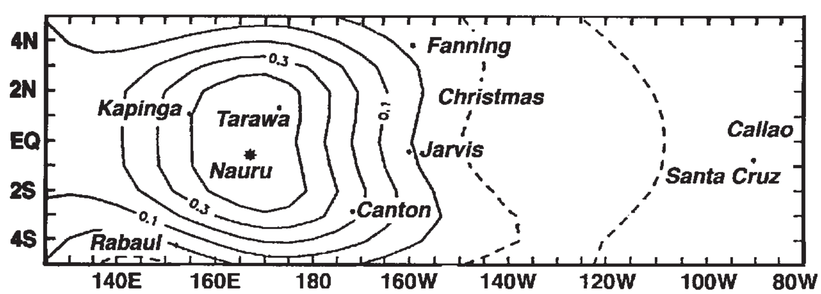

Figure 3 – Contour map of the influence of data from the tide gauge station at Nauru. In this experiment, data were also assimilated at Rabaul, Jarvis, Christmas, Santa Crux and Callao. [From Miller and Cane, 1996]

catalyzed tropical ocean data assimilation. Among these tropical ocean assimilations are some of the first applications of the Kalman filter to actual *in situ* ocean data, the methodology of which and related theoretical considerations for model-data synthesis are reviewed by Miller and Cane (1996) (Figure 3).

The third distinct objective of oceanic data assimilation, ocean and climate nowcasting and prediction, has not until recently been a topic of interest to mainstream oceanography. At present, however, more and more specific oceanographic applications find prediction not only timely but necessary. It is convenient to classify the oceanographic prediction problems by their time scale, as each of them requires different methodologies of approach and different data.

The problem of climate change is a prediction problem, and therefore needs to be treated as such. Simulation studies of climate change due to CO_2 increase and the greenhouse effect on a time scale of 50 to 100 years, have recently begun to use coupled atmospheric/ocean general circulation models (A/OGCM). The first studies that extended such coupled A/OGCM simulations to a multiple century time scale were those by Cusbasch *et al.* (1992) and by Manabe and Stouffer, (1994). Very recent studies simulating the coupled ocean/atmosphere system include those by Santer *et al.* (1995), Hergerl *et al.* (1996), Boville *et al.* (1998). The use of fully coupled A/OGCMs represents great progress from the time a few years ago when such studies were based on atmospheric models alone, were coupled to simple mixed-layer ocean models (as in Wilson and Mitchell, 1987, Schlesinger and Mitchell, 1987, Wetherald and Manabe, 1988, Washington and Meehl, 1989a), or were coupled to a model that parameterized heat transport below the mixed layer as a diffusive process (Hansen *et al.*, 1988). Studies using fully coupled A/OGCMs have taken one of two routes to initializing greenhouse warming simulations.

The first approach is to initialize the simulation with steady state solutions of the separate ocean and atmosphere sub models obtained by running the two models separately (Stouffer *et al.*, 1989; Manabe *et al.*, 1991; Cusbasch *et al.*, 1992; Manabe and Stouffer, 1994; Santer *et al.*, 1995). In this procedure the atmospheric model is spun up to a statistical steady state using prescribed SST climatology. The ocean model is then spun up using boundary conditions that restore the surface temperature and salinity to a similar climatology. The difference between the diagnosed heat and fresh water fluxes and the separate ocean and atmosphere spin-up runs is used to calculate “flux adjustment” fields. The two models are then coupled, and the flux correction fields are added to the ocean surface forcing at every time step during the subsequent long coupled integration. The flux adjustment, while clearly artificial and often of undesirably large amplitude, prevents the quite substantial drifts of the coupled system from the present climate which occur because the ocean steady solution is incompatible with the heat and fresh water fluxes provided by the atmospheric model. The initialization of coupled models with steady ocean solutions obtained by restoring the surface model fields of temperature and salinity to climatological data averaged over the last 40 years or more clearly leaves room for significant improvements. This initialization procedure ignores all the available data from the ocean interior. In addition, the use of many year averaged surface data sets results in a very artificial smoothing—and therefore distortion—of many important observed features of the oceanic circulation.

The second approach to greenhouse warming simulations is to initialize the model with the observed ocean climatology averaged over tens of years, without applying a flux correction to avoid a climate drift of the coupled system (Washington and Meehl, 1989; Boville *et al.*, 1998). This approach, while it avoids the artificial flux adjustment procedure, also suffers from a serious drawback. It is well known from numerical weather prediction that initializing a forecast with the raw data without any weight given to the model dynamics leads to severe initial “shocks” of the forecast model while it is adjusting to the initial conditions. Such a violent response may also be expected in the context of climate prediction as well, and may severely affect the model’s response to the greenhouse signal.

What is needed for the climate prediction problem is an assimilation approach that initializes the prediction simulation using a synthesis of the data and model results. The initialization should prevent initial shocks, yet constrain the initial condition using the available four-dimensional oceanic data base without the artificial smoothing of the temporal averaging procedure. Such an initialization may also reduce the climate drift of the coupled system, thus reducing the need for the artificial flux correction procedure.

Another coupled climate problem where prediction is needed is the decadal climate variability problem in which the ocean plays the major role. There are indications, for example, that variability of the North Atlantic thermohaline circulation affects the northern European climate on time scales of 10 to 30 years (Kushnir, 1994). The resulting climate and weather variability has important implications for atmospheric temperature and precipitation over vast regions. It is mostly controlled by oceanic processes, and its prediction is of obvious value. Forecasting decadal climate variability, like modeling the global greenhouse problem, needs to be done using coupled A/OGCMs, appropriate data sets, and assimilation methodology. The mechanisms of the thermohaline variability are still under investigation, with very diverse explanations offered so far, from strongly nonlinear mechanisms (Weaver *et al.*, 1991) suggesting the use of ocean-only model studies, to gentler, possibly linear mechanisms, based on coupled ocean-atmosphere model studies (Delworth *et al.*, 1993; Griffies and Tziperman, 1995). As the mechanism of this variability is not yet clear, data assimilation could be used to interpolate the little data that exist for this phenom-

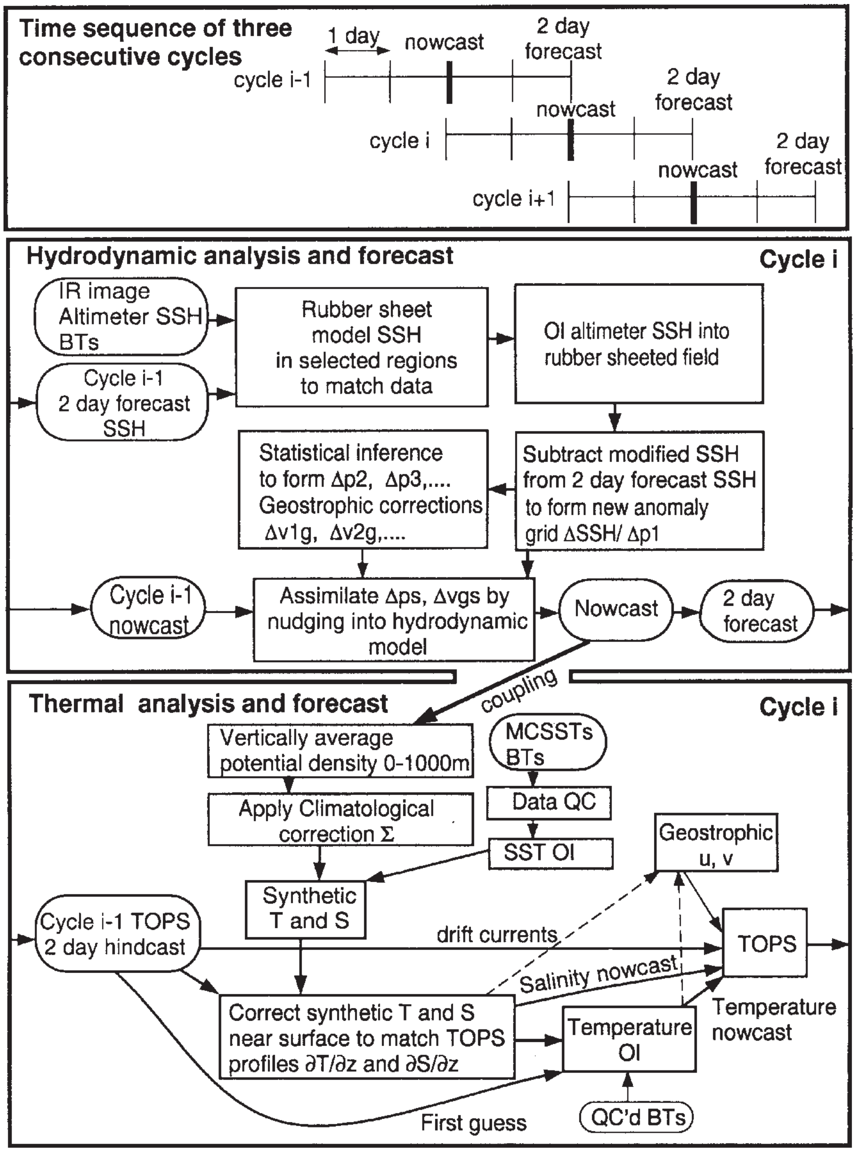

Fig. 4 – Schematic diagram of the North Pacific nowcast/forecast system. [From Carnes, *et al.,* 1996]

enon, and perhaps clarify the unresolved dynamical issues. The physical mechanisms of the decadal climate variability that results from fluctuations of the thermohaline circulation may have important implications for predicting this variability, yet practically no work has been carried out so far to address this issue as an assimilation and prediction problem.

The ocean/climate forecasting problem presenting the most successful application of data assimilation methods is the occurrence of El Niño-Southern Oscillations (ENSO) in the Pacific equatorial band every three to six years. The profound global socio-economic consequences of this phenomenon have attracted considerable attention in terms of pure modeling, data collection, and assimilation forecasting studies.

Barnett *et al.* (1988) discussed three different possible approaches to predicting the occurrences of ENSO. One forecasting scheme uses statistical models that rely on delayed correlations between various indicators in the Equatorial Pacific and the occurrence of ENSO (Barnett, 1984; Graham *et al.*, 1987). A second scheme uses a linear dynamical ocean model that is driven by the observed winds. In the forecast mode, the winds are assumed to remain constant beyond the last time for which observations are available, and the ocean model is integrated ahead for a few months to produce the forecast (Inoue and O'Brien, 1984). The third ENSO forecast scheme uses a simple coupled ocean atmosphere model with linear beta plane dynamics and a nonlinear equation for the SST evolution. The model is again initialized by running it with the observed winds, and then is integrated further to obtain the forecast (Cane *et al.*, 1986).

Remarkable progress has been made since the pioneering work of Barnett (1984) and Cane *et al.* (1986) with an emphasis on applying the most advanced OGCMs and assimilation schemes to the ENSO prediction problem. Until recently, in fact, simple coupled ocean-atmosphere models seemed to be more successful in ENSO forecasting, while fuller primitive equation models had serious difficulties in simulating, not to mention forecasting, ENSO events. The situation has changed. Full three-dimensional OGCMs coupled to similar AGCMs are now catching up with the simpler models. Miyakoda *et al.* (1989), for example, have been using such a coupled A/OGCM together with an OI assimilation method to forecast ENSO events. Better performance may be achieved by using schemes that assimilate all the available data, including interior ocean data for temperature, salinity and currents. This has been demonstrated by Ji *et al.* (1995). Another direction in which progress has been made is the development of more advanced assimilation methods such as Kalman filtering for this application. As in other applications discussed above, the ENSO prediction problem requires its own variant of these assimilation methodologies, based on the apparently chaotic character of ENSO dynamics (Burger and Cane, 1994; Burger *et al.*, 1995a,b).

Rosati *et al.* (1996) provide an important example of an oceanic four-dimensional data assimilation system developed on the global scale for use in initializing coupled A/OGCMs and to study interannual variability, with special focus on the tropical Pacific ocean examining El Niño signature. Leetma

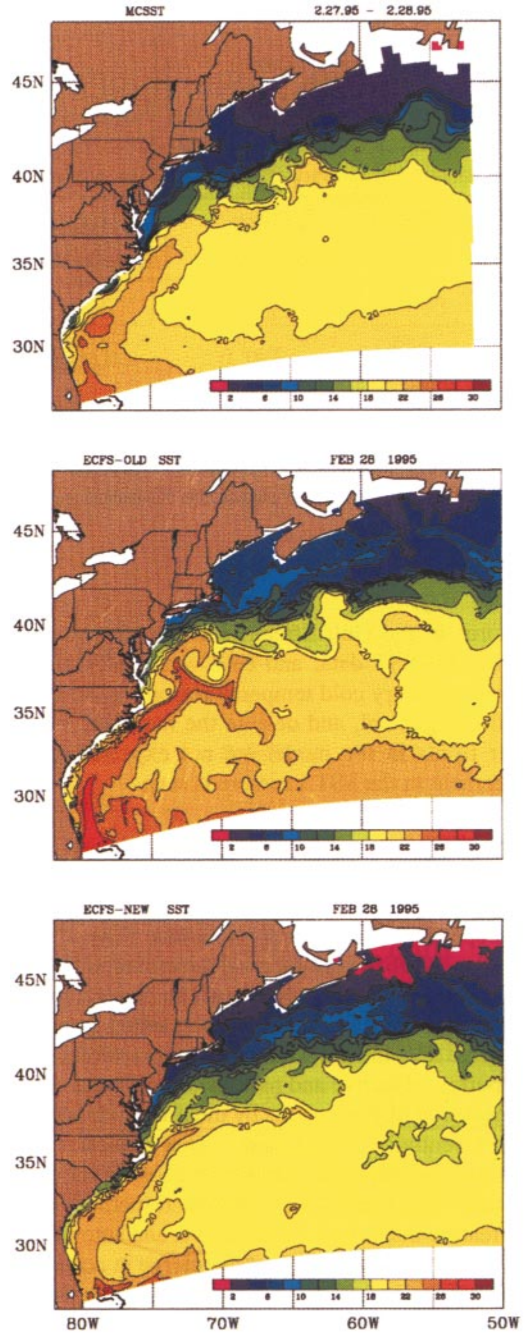

Fig. 5 – Observed (upper panel) and forecast (middle and lower panels) surface temperatures on 28 February 1995. The observed field is obtained from the analyzed MCSST product of NESDIS. The middle panel SST is obtained from the experimental model, where surface heat and momentum fluxes are obtained directly form the Eta model, and the lower panel is obtained from an updated forecast in which the heat and momentum fluxes are calculated from the lower layer atmospheric Eta fields. [From Aikman, *et al.*, 1996]

and Ji (1996) and Ji *et al.* (1996) also provide an example of an ocean data assimilation system developed as a component of a coupled A/OGCM to predict the ENSO phenomenon, but only for the tropical Pacific domain. The assimilation system synthesizes various datasets with the ocean model simulation to obtain analyses used for diagnostics and accurate forecast initialization. The outstanding success of the climate Prediction Center under the direction of Dr. Leeetma in predicting the exceptional 1997-1998 El Niño event demonstrates how essential the assimilation scheme has been for the El Niño forecast (Climate Prediction Center, National Centers for Environmental Prediction, 1998).

On a shorter time scale yet lies the problem of extended seasonal weather prediction, in which again the ocean plays a crucial role. In many situations a seasonal forecast of the expected amount of precipitation, for example, can have a significant impact on agricultural planning, especially but not exclusively in semi-arid regions. The application of coupled ocean-atmosphere GCMs to this problem is at its infancy, and the obvious need for such work can be expected to result in more efforts in this direction in the near future.

It is interesting to note that all the ocean forecasting problems surveyed so far involve using a coupled ocean-atmosphere model, rather than an ocean-only model. There are, however, situations in which ocean-only models can be utilized for relevant short-term assimilation and forecasting studies.

A first example for the ocean component alone is given by Carnes *et al.* (1996), who discuss an ocean modelling, data assimilation monitoring and prediction system developed for Naval operational use in the North Pacific ocean (Figure 4). Three-months long pseudo-operational forecasts are performed in the effort to address, among other issues, the problem of extended ocean prediction. A further example of forecasts on a very short time scale is provided by Aikman *et al.* (1996), in which a quasi-operational East Coast forecast system has been developed to produce 24-hour forecasts of water levels, currents, temperature and salinity in a coastal domain (Figure 5).

A final important example of the use of ocean-only models for the nowcasting and forecasting of oceanic flows is afforded by those ocean frontal systems of interest to navies, such as the prediction of the Gulf Stream front and its meandering on time scales of two to four weeks. The operational prediction of such synoptic oceanic motions is therefore a primary objective *per se* and a new profession—that of ocean forecaster—is rapidly emerging. Ocean forecasting involves real-time processing and assimilation of remote sensing data, and the production of timely forecasts of front locations and other eddy features in the ocean. A significant body of work has been developed in the last decade for this purpose, and use of such operational forecasting systems is fairly advanced. See, for instance, the issue of *Oceanography*, Vol. 5, no. 1, 1992, for a review of such operational forecasting systems in the world ocean, with a general discussion of the Navy Ocean Modeling and Prediction Program (Peloquin, 1992) and the interesting DAMEÉ-GSR (Data Assimilation Model Evaluation Experiments – Gulf Stream Region) effort in the Gulf

Stream System involving the assessment of 4 different models through prediction evaluation experiments (Leese *et al.*, 1992; see also Ezer *et al.*, 1992; Ezer *et al.*, 1993; Willems *et al.*, 1994; Malanotte-Rizzoli and Young, 1997). The DAMEÉ-GSR effort was successively extended to the North Atlantic Basin, DAMEÉ–NAB, with similar comparisons of different models in assimilation mode. A special issue of *Deep-Sea Research* will be dedicated to DAMEÉ-NAB.

Robinson (1992) and Robinson *et al.* (1996) discuss real-time regional forecasting carried out in different areas of the world-ocean. They illustrate the use and limitations of this methodology with practical examples using both a primitive equation and an open ocean quasi-geostrophic model. The latter constitutes by itself a flexible and logistically portable open-ocean forecasting system that has been tested in 11 sites of the world ocean comprising frontal systems. All the tests were real-time forecasts, and for six of them the forecasts were carried out aboard ships.

Conclusions

Having considered some of the objectives of ocean data assimilation, it is quite surprising to realize how much work still remains to meet them. Much of the effort presently invested in oceanographic data assimilation lies in the development of appropriate methodologies that would enable us to approach the objectives discussed above. The diversity of these objectives clearly indicates that no single assimilation methodology can address all of the needs. It is more likely that several techniques, such as the Kalman Filter, the Adjoint Method, and Optimal Interpolation, will be the main candidates for addressing the future needs of oceanographic assimilation. Each methodology will be used for the specific goals to which it is best suited.

With ample motivation for the synthesis of fully complex OGCMs and oceanic data, and with new observational techniques and global observational programs being developed, further developments in oceanic data assimilation are essential. Even though the field has grown impressively in the last decade, the needs of oceanic data assimilation still surpass the effort so far invested, and further significant growth is still necessary.

References

1. F. Aikman III, G.L. Mellor, T. Ezer, D. Sheinin, P. Chen, L. Breaker and D.B. Rao, "Towards an operational nowcast/forecast system for the U.S. East Coast," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanography Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 374-376.

2. R.A. Anthes, "Data assimilation and initialization of hurricane prediction models," *J. Atmospheric Sciences*, **31**, 701-719 (1974).

3. The ATOC Consortium, "The North Pacific general circulation from altimetry, acoustic tomography and a general circulation model," *Science*, **281**, 1327-1332 (1998).

4. T. Barnett, "Prediction of the El Nino of 1982-83," *Monthly Weather Review*, **112**, 1403-1407 (1984).

5. T. Barnett, N. Graham, M.A. Cane, S. Zebiak, S. Dolan, J. O'Brien and D. Legler, "On the prediction of the El Nino of 1986-1987," *Science*, **241**, 192-196 (1988).

6. C. Bengtsson, M. Ghil and E. Kallen (eds.), *Dynamic Meteorology: Data Assimilation Methods*, (Springer-Verlag, New York, 1981), p. 330.

7. A.F. Bennett, *Inverse methods in physical oceanography*, (Cambridge Monographs, Cambridge University Press, 1992), p. 346.

8. A. Bergamasco and P. Malanotte-Rizzoli, "The seasonal steady circulation of the Eastern Mediterranean determined with the adjoint method," *Deep-Sea Research*, **40**, 1269-1298 (1993).

9. C.W. Böning, W.R. Holland, F.O. Bryan, G. Danabasoglu and J. McWilliams, "An overlooked problem in the model simulation of the thermohaline circulation and heat transport in the Atlantic Ocean," *J. Climatology*, **8**, 515-523 (1995).

10. B.A. Boville and P.R. Gent, "The NCAR Climate System model, version one," *J. Climatology*, **11**, 1115-1130 (1998).

11. K. Bryan, "A numerical method for the study of the circulation of the world ocean," *J. Computational Physics*, **4**, 347-376 (1969).

12. F. Bryan, "Parameter sensitivity of primitive equation ocean general circulation models," *J. Physical Oceanography*, **17**, 970-985 (1987).

13. G. Burger and M.A. Cane, "Interactive Kalman filtering," *J. Geophysical Research*, **99**(C4), 8,015-8,031 (1994).

14. G. Burger, S.E. Zebiak and M.A. Cane, "Quasi-fixed points and periodic orbits in the Zebiak-Cane ENSO model with applications in Kalman filtering. Part I: monthly quasi-fixed points," *Monthly Weather Review*, **123**, 2,802-2,813 (1995a).

15. G. Burger, S.E. Zebiak and M.A. Cane, "Quasi-fixed points and periodic orbits in the Zebiak-Cane ENSO model with applications in Kalman filtering. Part II: periodic orbits," *Monthly Weather Review*, **123**, 2,814-2,824 (1995b).

16. A.J. Busalacchi, "Data assimilation in support of tropical ocean circulation studies," *Modern approaches to data assimilation in ocean modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 235-270.

17. M.A. Cane, S.E. Zebiak and S.C. Dolan, "Experimental forecast of El Nino," *Nature*, **321**, 827 (1986).

18. M.A. Cane, A. Kaplan, R.N. Miller, B. Tang, E. Hackert and A.J. Busalacchi, "Mapping tropical Pacific sea level: data assimilation via a reduced state space Kalman filter," *J. Geophysical Research*, **101**, 22,599-22,617 (1996).

19. A. Capotondi, P. Malanotte-Rizzoli and W.R. Holland, "Assimilation of altimeter data into a quasi-geostrophic model

of the Gulf Stream system, Part I: dynamical considerations," *J. Physical Oceanography*, **25**, 1,130-1,152 (1995a).

20. A. Capotondi, W.R. Holland and P. Malanotte-Rizzoli, "Assimilation of altimeter data into a quasi-geostrophic model of the Gulf stream system, Part II. Assimilation results," *J. Physical Oceanography*, **25**, 1,153-1,173 (1995b).

21. M.R. Carnes, D.N. Fox, R.C. Rhodes and O.M. Smedstad, "Data assimilation in the North Pacific Ocean monitoring and prediction system," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanography Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 319-346.

22. D.C. Chapman, "Numerical treatment of cross-shelf open boundaries in a barotropic coastal ocean model," *J. Physical Oceanography*, **15**, 1,060-1,075 (1985).

23. Climate Prediction Center, "Activities during the 1997-98 El Nino/Southern Oscillation Event," *NCEP Report*, p. 77 (1998).

24. B.D. Cornuelle and P.F. Worcester, "Ocean Acoustic Tomography: Integral data and ocean models" *Modern Approaches to data assimilation in ocean modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli, (ed.), (Elsevier, New York, 1996), **61**, 97-118.

25. U. Cusbasch, K. Hasselmann, H. Hock, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer and R. Sansen, "Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model," *Climate Dynamics*, **8**, 55-69 (1992).

26. R. Daley, *Atmospheric Data Analysis*, (Cambridge University Press, 1991), p. 497.

27. T. Delworth, S. Manabe and R.J. Stouffer, "Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model," *J. Climatology*, **12**, 1,993-2,011 (1993).

28. J.C. Derber and A. Rosati, "A global ocean data assimilation system," *J. Physical Oceanography*, **19**, 1,333-1,347 (1989).

29. T. Ezer, D.S. Ko and G.L. Mellor, "Modeling and forecasting the Gulf Stream," *Marine Technical Society Journal*, **26**, 5-14 (1992).

30. T. Ezer, G.L. Mellor, D.S. Ko and Z. Sirkes, "A comparison of Gulf Stream sea surface height field derived from GEOSAT altimeter data and those derived from sea surface temperature data," *J. Atmospheric Oceanic Technology*, **10**, 76-87 (1993).

31. L.L. Fu and I. Fukumori, "A case study of the effects of errors in satellite altimetry on data assimilation," *Modern approaches to data assimilation in ocean modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 77-96.

32. I. Fukumori, J. Benveniste, C.I. Wunsch and D.B. Haidvogel, "Assimilation of sea surface topography into an ocean circulation model using a steady state smoother," *J. Physical Oceanography*, **23**, 1,831-1,855 (1993).

33. I. Fukumori and P. Malanotte-Rizzoli, "An approximate Kalman filter for ocean data assimilation: a reduced-dimension, static, linearized Kalman filter," *J. Geophysical Research*, **100**, 6,777-6,793 (1995).

34. A. Ganachaud, C.I. Wunsch, M.C. Kim and B. Tapley, "Combination of TOPEX/POSEIDON data with a hydrographic inversion for the determination of the oceanic general circulation," *Geophysical Journal International*, **128**, 708-722 (1997).

35. P.R. Gent and J.C. McWilliams, "Isopycnal mixing in ocean circulation models," *J. Physical Oceanography*, **20**, 150-155 (1990).

36. M. Ghil and P. Malanotte-Rizzoli, "Data assimilation in meteorology and oceanography," *Advances in geophysics*, B. Saltzmann (ed.), **33**, 141-266 (1991).

37. N.E. Graham, J. Michaelsen and T.P. Barnett, "An investigation of the El Nino-Southern Oscillation cycle with statistical models. I. Predictor field characteristics," *J. Geophysical Research*, **92**, 14,251-14,270 (1987).

38. J. Green, "Transfer properties of the large-scale eddies and the general circulation of the atmosphere," *Royal Meteorological Society Quarterly Journal*, **96**, 157-185 (1970).

39. M.S. Griffies and E. Tziperman, "A linear thermohaline oscillator driven by stochastic atmospheric forcing, *J. Climatology*," **8**, 2,440-2,453 (1995).

40. J.R. Gunson and P. Malanotte-Rizzoli, "Assimilation studies of open-ocean flows. Part I: Estimation of initial and boundary conditions," *J. Geophysical Research*, **101**, 28,457-28,472 (1996a).

41. J.R. Gunson and P. Malanotte-Rizzoli, "Assimilation studies of open-ocean flows. Part II: Error measures with strongly nonlinear dynamics," *J. Geophysical Research*, **101**, 28,473-28,488 (1996b).

42. D.B. Haidvogel and A.R. Robinson (eds.), *Dynamics Atmospheres Oceans*, Special Issue on Data Assimilation, **13**(3-4), (1989).

43. M.C.B. Hall and D.G. Cacuci, "Physical interpretation of the adjoint functions for sensitivity analysis of atmospheric models," *J. Atmospheric Sciences*, **40**, 2,537-2,546 (1983).

44. J. Hansen, I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell and P. Stone, "Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model," *J. Geophysical Research*, **93**, 9,341-9,364 (1988).

45. G.C. Hegerl, H. von Storch, K. Hasselmann, B.D. Santer, U. Cusbasch and P.D. Jones, "Detecting greenhouse-gas induced climate change with an optimal fingerprint method," *J. Climatology*, **9**, 2,281-2,306 (1996).

46. N.G. Hogg, "Oceanographic data for parameter estimation," *Modern approaches to data assimilation in ocean modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 57-76.

47. W.R. Holland and A. Capotondi, "Recent developments in prognostic ocean modelling," *Modern approaches to data assimilation in ocean modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 21-56.

48. W.R. Holland and A.D. Hirschman, "A numerical calculation

of the circulation in the North Atlantic Ocean," *J. Physical Oceanography*, **2**, 336-354 (1972).

49. W.R. Holland and P. Malanotte-Rizzoli, "Assimilation of altimeter data into an ocean circulation model: space versus time resolution studies," *J. Physical Oceanography*, **19**, 1,507-1,534 (1989).

50. M. Inoue and J.J. O'Brien, "A forecasting model for the onset of a major El Nino," *Monthlty Weather Review*, **112**, 2,326-2,337 (1984).

51. M. Ji, A. Leetmaa and J. Derber, "An ocean analysis for seasonal to interannual climate studies," *Monthly Weather Review*, **123**, 460-481 (1995).

52. M. Ji, A. Leetmaa and V.E. Kousky, "Coupled model forecasts of ENSO during the 1980's and 1990's at the National Meteorological Center," *J. Climatology*, **9**, 3,105-3,120 (1996).

53. S. Jiang, P.H. Stone and P. Malanotte-Rizzoli, "An assessment of the GFDL ocean model with coarse resolution. Part I: Annual Mean Climatology," *J. Geophysical Research*, in press (1999).

54. Y. Kushnir, "Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions," *J. Climatology*, **7**, 141-157 (1994).

55. T. Lee and J. Marotzke, "Inferring meridional mass and heat transports in the Indian Ocean by combining a general circulation model with climatological data," *J. Geophysical Research*, **102**, 10,585-10,602 (1997).

56. T. Lee and J. Marotzke, "Seasonal cycles of meridional overturning and heat transport of the Indian Ocean," *J. Physical Oceanography*, **28**, 923-943 (1998).

57. J.A. Leese, R.C. Willems and L.A. Yeske, "Evaluation capability for the Navy Ocean Modeling and Prediction Program," *Oceanography*, **1**, 55-59 (1992).

58. A. Leetma and M. Ji, "Ocean data assimilation as a component of a Climate Forecast System," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanography Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 271-296.

59. P. Malanotte-Rizzoli and R.E. Young, "Assimilation of global versus local datasets into a regional model of the Gulf Stream system, Part I: Data effectiveness," *J. Geophysical Research*, **100**, 24,773-24,796 (1995).

60. P. Malanotte-Rizzoli and R.E. Young, "Gulf Stream system assimilation experiments: a sensitivity study," *J. Atmospheric Oceanic Technology*, **14**, 1,392-1,408 (1997).

61. S. Manabe, R.J. Stouffer, M.J. Spelman and K. Bryan, "Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO_2, Part I: annual mean response," *J. Climatology*, **4**, 785-818 (1991).

62. S. Manabe and R.J. Stouffer, "Multiple-century response of a coupled ocean-amosphere model to an increase of atmospheric carbon dioxide," *J. Climatology*, **7**, 5-23 (1994).

63. J. Marotzke, "The role of integration time in determining a steady state through data assimilation," *J. Physical Oceanography*, **22**, 1,556-1,567 (1992).

64. J. Marotzke and C. Wunsch, "Finding the steady state of a general circulation model through data assimilation: application to the North Atlantic Ocean," *J. Geophysical Research*, **98**, 20,149-20,167 (1993).

65. J. Marotzke, R. Giering, Q.K. Zhang, D. Stammer, C. Hill and T. Lee, "Construction of the adjoint MIT ocean general circulation model and application to Atlantic heat transport sensitivity," *J. Geophysical Research*, submitted (1999).

66. G.L. Mellor and T. Yamada, "Development of a turbulence closure model for geophysical fluid problems," *Reviews Geophysics Space Physics*, **VOLUME**, 20,851-20,875 (1982).

67. G.L. Mellor and T. Ezer, "A Gulf Stream model and an altimeter assimilation scheme," *J. Geophys. Res.*, **96**, 8,779-8,795 (1991).

68. D. Menemenlis, A.T. Webb, C.I. Wunsch, U. Send and C. Hill, "Basin scale ocean circulation from combined altimetry, tomography and model data," *Nature*, **385**, 618-621 (1997a).

69. D. Menemenlis, P. Fieguth, C.I. Wunsch and A. Willsky, "Adaptation of a fast optimal interpolation algorithm to the mapping of oceanographic data," *J. Geophysical Research*, **102**, 10,573-10,584 (1997b).

70. W. Menke, *Geophysical Data Analysis: Discrete Inverse Theory*, (Academic Press, 1984), p. 284.

71. R.N. Miller and N.A. Cane, "Tropical data assimilation: theoretical aspects," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanograhic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 207-234.

72. K. Miyakoda, J. Sirutis, A. Rosati and R. Gudgel, *Proceedings of Workshop on Japanese coupled ocean-atmosphere response experiments*, A. Sumi (ed.), 23-24 October 1989, p. 93.

73. W.H. Munk, P.F. Worcester and C.I. Wunsch, *Ocean Acoustic Tomography*, (Cambridge University Press, 1995), p. 433.

74. *Oceanography*, **5**(1), 80 pages, (1992).

75. R.A. Peloquin, "The navy ocean modeling and prediction program," *Oceanography*, **1**, 4-8 (1992).

76. A.R. Robinson, H.G. Arango, A. Warm-Varmas, W. Leslie, A.J. Miller, P.J. Haley and C.J. Lozano, "Real-time Regional Forecasting," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanography Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 377-412.

77. A.R. Robinson, "Shipboard prediction with a regional forecast model," *Oceanography*, **1**, 42-48 (1992).

78. A.R. Robinson, M.A. Spall, L.F. Walstad and W.G. Leslie, "Data assimilation and dynamical interpolation in Gulfcast experiments," *Dynamic Atmospheric Oceans*, **13**, 269-300 (1989).

79. A. Rosati, R. Gudgel and K. Miyakoda, "Global Ocean Data Assimilation system," *Modern approaches to data assimilation*

in ocean modeling, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 181-206.

80. B.D. Santer, K. Taylor, T. Wigley, J. Penner, P. Jones and U. Cusbasch, "Towards the detection and attribution of an anthropogenic effect on climate," *Climate Dynamics*, **12**, 77-100 (1995).

81. J.L. Sarmiento and K. Bryan, "An ocean transport model for the North Atlantic," *J. Geophysical Research*, **93**, 10,655-10,665 (1982).

82. M.E. Schlesinger and J.F.B. Mitchell, "Climate model simulations of the equilibrium climatic response to increased carbon dioxide," *Reviews Geophysics*, **25**, 760-798 (1987).

83. R.W. Schmitt, P.S. Bogden and C.E. Dorman, "Evaporation minus precipitation and density fluxes for the North Atlantic," *J. Physical Oceanography*, **19**, 1,208-1,221 (1989).

84. Z. Sirkes, E. Tziperman and W.C. Thacker, "Combining data and a Global Primitive Equation Ocean General Circulation model using the adjoint method," *Modern Approaches to Data Assimilation in Ocean Modeling*, Elsevier Oceanographic Series, P. Malanotte-Rizzoli (ed.), (Elsevier, New York, 1996), **61**, 119-146.

85. D. Stammer and C. Wunsch, "Preliminary assessment of the accuracy and precision of TOPEX/POSEIDON altimeter data with respect to the large-scale ocean circulation," *J. Geophysical Research*, **99**, 29,584-29,604 (1994).

86. D. Stammer and C. Wunsch, "The determination of the large-scale circulation of the Pacific ocean from satellite altimetry using model Green's functions," *J. Geophysical Research*, **101**, 18,409-18,432 (1996).

87. D. Stammer, C.I. Wunsch, R. Goering, Q.K. Zhang, J. Marotzke, J. Marshall and C.N. Hill, "The global ocean circulation estimated from TOPEX/POSEIDON altimetry and the MIT general circulation model," *MIT Center for Global Change Science*, *Report No. 49*, p. 40 (1997).

88. P.H. Stone, "A simplified radiative-dynamical model for the static stability of rotating atmospheres," *J. Atmospheric Sciences*, **29**, 405-418 (1972).

89. R.J. Stouffer, S. Manabe and K. Bryan, "Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO_2," *Nature*, **342**, 660-662 (1989).

90. Tarantola, *Inverse problems theory, Methods for data fitting and model parameter estimation*, (Elsevier Science Publ., 1987), p. 613.

91. W.C. Thacker, "Fitting models to data by enforcing spatial and temporal smoothness," *J. Geophysical Research*, **93**, 10,655-10,665 (1988).

92. W.C. Thacker and R.B. Long, "Fitting dynamics to data," *J. Geophysical Research*, **93**, 1,227-1,240 (1988).

93. K.E. Trenberth, J.G. Olson and W.G. Large, "A global ocean wind stress climatology based on ECMWF analysis," *NCAR/TN-338+STR*, p. 93 (1989).

94. R.E. Trenberth and A. Solomon, "The global heat balance: heat transports in the atmosphere and ocean," *Climate Dynamics*, **9**, 107-134 (1994).

95. E. Tziperman and W.C. Thacker, "An optimal control/adjoint equation approach to studying the oceanic general circulation," *J. Physical Oceanography*, **19**, 1,471-1,485 (1989).

96. E. Tziperman, W.C. Thacker, R.B. Long and S.M. Hwang, "Oceanic data analysis using a general circulation model, Part I: Simulations," *J. Physical Oceanography*, **22**, 1,434-1,457 (1992a).

97. E. Tziperman, W.C. Thacker, R.B. Long, S.M. Hwang and S.R. Rintoul, "Oceanic data analysis using a general circulation model, Part II: A North Atlantic model," *J. Physical Oceanography*, **22**, 1,458-1,485 (1992b).

98. J. Verron, L. Gourdeau, D.T. Pham, R. Murtugudde and A.J. Busalacchi, "An extended Kalman filter to assimilate satellite altimeter data into a non-linear numerical model of the tropical Pacific ocean: method and validation," *J. Geophysical Research*, submitted (1999).

99. M. Visbeck, J. Marshall and H. Jones, "Dynamics of Isolated Convective Regions of the Ocean," *J. Physical Oceanography*, **26**, 1,721-1,734 (1996).

100. W.M. Washington and G.A. Meehl, "Seasonal cycle experiments on the climate sensitivity due to a doubling of CO_2 with an atmospheric general circulation model coupled to a simple mixed layer ocean model," *J. Geophysical Research*, **89**, 9,475-9,503 (1989).

101. W.M. Washington, G.A. Meehl, L. VerPlant and T.W. Bettge, "A world ocean model for greenhouse sensitivity studies: resolution intercomparison and the role of diagnostic forcing," *Climate Dynamics*, in press (1999).

102. A.J. Weaver, E.S. Sarachik and J. Marotzke, "Freshwater flux forcing of decadal and interdecadal oceanic variability," *Nature*, **353**, 836-838 (1991).

103. R.T. Wetherald and S. Manabe, "Cloud feedback processes in a general circulation model," *J. Atmospheric Sciences*, **45**, 1,397-1,415 (1988).

104. R.G. Willems, S.M. Glenn, M.R. Crowley, P. Malanotte-Rizzoli, R.E. Young, T. Ezer, G. Mellor, H.G. Arango, A.R. Robinson and C.C.A. Lai, "Experiment evaluates ocean models and data assimilation in the Gulf Stream," *Earth Ocean Sciences*, *Transactions*, American Geophysical Union, **75**(34), 385-394 (1994).

105. C.A. Wilson and J.F.B. Mitchell, "A doubled CO_2 climate sensitivity experiment with a global climate model including a simple ocean," *J. Geophysical Research*, **92**, 13,315-13,343 (1987).

106. C.I. Wunsch, "The general circulation of the North Atlantic west of 50 degrees W determined from inverse methods," *Reviews Geophysics Space Physics*, **16**, 583-620 (1978).

107. C.I. Wunsch, "Using data with models, ill-posed and time-dependent ill-posed problems" *Geophysical Tomography*, Y. Desaubies, A. Tarantola and J. Zinn-Justin (eds.), (Elsevier Publ. Company, 1989a), pp. 3-41.

108. C.I. Wunsch, "Tracer inverse problems," *Oceanic circulation*

models: combining data and dynamics, D.L.T. Anderson and J. Willebrand, (eds.), (Kluwer Academic Publ., 1989b), pp. 1-78.

109. C.I. Wunsch, *The Ocean Circulation Inverse Problem*, (Cambridge University Press, 1996), p. 437.

110. C.I. Wunsch and B. Grant, "Towards the general circulation of the North Atlantic Ocean," *Progress in Oceanography*, **11**, 1-59 (1982).

111. L. Yu and P. Malanotte-Rizzoli, "Analysis of the North Atlantic climatologies using a combined OGCM/adjoint approach," *J. Marine Research*, **54**, 867-913 (1996).

112. L. Yu and P. Malanotte-Rizzoli, "Inverse modeling of seasonal variability in the North Atlantic Ocean," *J. Physical Oceanography*, **28**, 902-922 (1998).

113. K.Q. Zhang and J. Marotzke, "The importance of open-boundary estimation for an Indian Ocean GCM-data synthesis," *J. Marine Research*, in press (1995).

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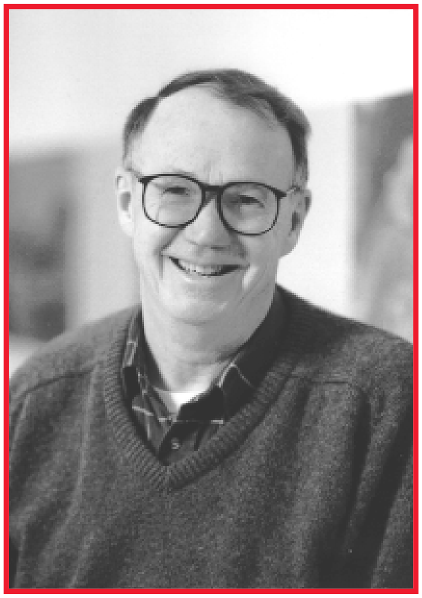
Profiles in Science



Dr. George Mellor
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After an initial career in aerodynamics, George Mellor turned his scientific interests to atmospheric and oceanic turbulent boundary layers. He established the Program in Atmospheric and Oceanic Sciences at Princeton University, which is associated with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). Mellor's research involves the study of estuarine and oceanic dynamics through the use of numerical ocean models. Professor Mellor is the author of more than one hundred journal articles covering turbulent boundary layers, ocean modeling and other topics in fluid dynamics and a textbook on Introductory Oceanography. He is a fellow of the American Meteorological Society and the American Geophysical Union. The Princeton Ocean Model (POM), developed by Mellor and Alan Blumberg in the 1970s, is used widely by scientists, institutions and industry, including the U.S. Navy, NOAA's National Environmental Center and the National Ocean Service.There is an internet users group of over 350 users worldwide. POM includes an imbedded second moment turbulence closure sub-model to provide vertical mixing coefficients, a sigma vertical coordinate scaled on water depth, orthogonal curvilinear horizontal coordinates and an "Arakawa C" finite differencing scheme. The horizontal grid differencing is explicit whereas the vertical differencing is implicit. The latter eliminates time constraints for the vertical coordinate and permits the use of fine vertical resolution in the surface and bottom boundary layers. The model has a free surface and a split time step. Complete thermodynamics have been implemented. The turbulence closure sub-model is often cited in the literature as the Mellor-Yamada turbulence closure model, but the model is based on turbulence hypotheses by Rotta and Kolmogorov which were extended to stratified flow.

Current users of POM are the beneficiaries of forty years of research. The branch of this evolution at Princeton is illustrative. In the 1960s, turbulent boundary layer experiments and models were investigated by H.J. Herring and students. In 1969, GFDL was established at Princeton under J. Smagorinsky. In the early 1970s, T.Yamada developed atmospheric boundary layer formulations accounting for turbulence. In the late 1970s based on these advances, the first version of POM was created by G. Mellor and A. Blumberg. From 1980-83, Dynalysis, a company formed by Blumberg and Herring, applied POM to Gulf of Mexico circulation studies. Simultaneously, L-Y Oey modeled the Hudson/Raritan Estuary. Since the mid-80s, improved versions of POM have been developed for Delaware Bay (Galparin), the Arctic Ocean (Kantha, Hakkinen), the Mediterranean Sea (Zavatarelli), the North Atlantic (Ezer) and the coastal zone of the eastern United States (Aikman).

Further information including a list of journal publications can be found in http://www.aos.princeton.edu/wwwpublic/htdocs.pom/

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